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## ORE DEPOSITION IN THE BOLIVIAN TIN-SILVER DEPOSITS.


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### INTRODUCTION.

The last twenty-five years have witnessed rapid strides in the development of the tin veins of the Bolivian cordillera. Once confined largely to the silver-rich ores of what is now the southern portion of the district, the range of known deposits has been steadily expanded until this distinct metallogenetic province extends over six degrees of latitude and embraces many veins of widely differing characteristics. The variety of types and relations progressively revealed has been closely paralleled by a

variety of genetic theories, each in turn founded upon more comprehensive information than was its predecessor.

Considering only the complex sulphide ores of silver, tin, and bismuth associated with igneous rocks, consolidated at no more than moderate depths, Stelzner[1] regarded the Bolivian tin deposits, to which he applied the name *Typus Potosi,* as complete exceptions to the normal occurrences of tin with granite throughout the world, and attributed to them solely a hydrothermal origin.

He knew of the existence of predominant tin veins in the north and also of their association, geographically at least, with the granite core of the Cordillera Real. He did not know that such high temperature minerals as tourmaline and topaz were present, and he accepted and reaffirmed the antiquity of the granite relative to the age of ore deposition. Stelzner thereby fixed upon mining and geological opinion the impression that these tin veins differed fundamentally from previously known occurrences in lacking high temperature or "pneumatolitic" characteristics. A review of the literature reveals no evidence for the commonly repeated Paleozoic age of the granite of the region. Many of the invaded rocks are, no doubt, Silurian and Devonian sedimentaries, but, as we shall see, there are as good or better lines of reasoning pointing to a much more recent origin for the granite as well as the elevation of the Bolivian cordillera.

When the pronounced difference in the character of the cassiterite veins and the complex silver-tin veins compelled recognition in any tenable theory, Steinmann[2] attempted to explain everything as centering about the latter, better-known type. The cassiterite, quartz, pyrite association was classed as an outlying facies of the mineralization, deposited at a greater distance from the source than the silver-bearing sulphide ores. In the light of present-day interpretation of the relations between temperature and ore deposition, this theory finds no adherents and will be shown to be contrary to facts in the course of this paper.

[1] Stelzner, A. W., "Die Silber-Zinnerzlagerstätten Bolivias," *Zeitschrift der deutschen geologischen Gesellschaft,* vol. 49, pp. 51–142, 1897.

[2] Steinmann, G., "Die Zinnerzlagerstätten Bolivias," *Zeitschrift der deutschen geologischen Gesellschaft,* vol. 59, Protokoll, pp. 7–9, 1907.

Later Rumbold[3] and Armas[4] emphasized the presence of abundant tourmaline in certain of the northern cassiterite veins and on the strength of this occurrence of a recognized high temperature gangue mineral, postulated a "pneumatolitic" origin for the deposits. Armas suggested that there had been a reopening of the veins accompanied by deposition of the silver minerals.

In 1912 Singewald[5] pointed out the inadequacy of each previous theory to account for all of the facts, and advanced the first plausible explanation covering the two types of deposits. He accepted Steinmann's view of a common genetic source for all of the ore solutions, but wisely reversed the former interpretation of the relations between the cassiterite and the complex sulphide veins. In brief, he classifies the latter type of mineralization as that of the intermediate vein zone and the former as that of a slightly higher temperature facies. He does not consider that characteristic high temperature tin deposits occur in the district.

Seven years later Miller[6] and Singewald restated the same theory in their book on South American mining districts. To quote the authors: "It is futile to attempt to establish an exact correspondence between these veins (Bolivian) and tin veins of the type represented by those of Saxony and Cornwall;" and "Inasmuch as the characteristics of the deep vein zone are but feebly developed in the most pronounced tin vein type, and the characteristics of the more pronounced silver vein type are those of deposits formed at moderate depths, and because further the texture of the genetically related igneous rocks is that of rocks which solidified at not greater than moderate depths, it appears

[3] Rumbold, William R., "The Origin of the Bolivian Tin Deposits," ECON. GEOL., vol. 4, pp. 321–364, 1909.

[4] Armas, M., "Genesis of Bolivian Tin Deposits," *Eng. and Min. Jour.*, vol. 29, pp. 311–314, 1911; "Etude sur l' étain et l' or en Bolivie et sur le genèsé des dépots stannifères," *Annales des Mines*, 10th Ser., vol. 20, pp. 149–230, 1911.

[5] Singewald, Joseph T., Jr., "Some Genetic Relations of Tin Deposits," ECON. GEOL., vol. 7, pp. 263–279, 1912.

[6] Miller, B. L., and Singewald, J. T., Jr., "The Mineral Deposits of South America," McGraw-Hill Book Co., New York, 1919, pp. 94–100.

certain that ore deposition took place under conditions of temperature and pressure prevailing at moderate depths." To many readers this statement of the case, though fitting many of the facts and inspiring conviction, must remain partially unsatisfactory in that such minerals as tourmaline, topaz, and apatite are assigned in abundance to the intermediate vein zone. Such exceptional occurrences constitute a serious obstacle to placing these deposits in their natural position in the genetic classification of mineral deposits, and in removing this obstacle it is hoped that an advance, however slight, will be made toward an orderly arrangement of our knowledge of ore deposition.

The author became interested in the Bolivian tin ores during some months spent in the Andes several years ago. Specimens examined at that time and descriptions of the districts received from mining men of the region first suggested the outline of this thesis. Though an unexpectedly early return to the United States prevented a study of the deposits in the field, the problem was kept in mind and the re-statement of Singewald's early theory quoted in the foregoing paragraph has influenced the writer to publish this paper. Two suites of specimens studied recently in connection with ore dressing tests have supplied important genetic evidence, and a fine collection of tin ores presented to the Massachusetts Institute of Technology by Mr. Howland Bancroft has made it possible to broaden the scope of the work to include a general microscopic description of the ore minerals and their relations.

In short, the author proposes to prove that a normal and expected sequence of types follows a normal sequence of temperature conditions. The characteristics of the deep vein zone are very typically developed in the most pronounced tin vein type. This type is genetically connected with typical granitic rocks which probably solidified at considerable depth and ore deposition here took place under conditions characteristic of the high temperature zone. The associated igneous rocks and the features of the mineralization conform closely to those of other high temperature tin veins throughout the world. The characteristics

of the more pronounced silver vein type are those of moderate depths, the geneticaly related igneous rocks are in all cases those solidifying at no more than moderate depths, and ore deposition took place under conditions characteristic of the intermediate vein zone. Furthermore there are deposits whose mineralization points to conditions intermediate between the above two, as is to be expected in so extensive a province where any and all conditions awaited the introduction of the ore solutions.

## GENERAL GEOGRAPHY AND GEOLOGY.

The tin deposits of Bolivia extend along the lines of the Cordillera Real and its southeastward extension from north of La Paz to the southeastern part of the department of Potosi. The mines are at elevations from about twelve thousand feet to nearly twenty thousand feet, the higher ones especially, being in rugged, wind-swept, and snow-clad country where none but the native Indian can work.

*The Granite Core.*—The granite core of the range is flanked by shales, sandstones, conglomerates, and quartzites, which in many cases abut sharply against the contact, and into which the granite has sent numerous apophyses and dikes of porphyry. The relations of the granite to the sedimentaries are clearly those of intrusion. South of Quimsa Cruz exposures of the granite core have been recorded only in small areas several miles from Potosi. There are innumerable exposures of porphyries throughout the southern district similar in nature to the porphyries associated with the granite in the north, and there seems good reason to believe that the granite extends southward under the sedimentaries and more recent igneous flows. An examination of the topography indicates that the southern area, as lofty as it is, lacks the sharp ruggedness of Illampu and Illimani in the northern granite area, and suggests that the top of the great batholith reached higher levels in the north, with subsequent more rapid removal of the covering material.

*Age of Intrusions.*—The intruded sediments have been identified as Silurian and Devonian from their fossil content in the

north where found with granite. Similar appearing rocks intruded by the porphyry in the south were long considered to be of the same age, but in the vicinity of Potosi the shales seem to have been definitely fixed as late Tertiary. Miller[7] and Singewald summarize the evidence on this point, including their own discovery of a marine brachiopod of Miocene or Pliocene age and other findings of Pliocene flora in the plant-bearing beds intruded by the porphyry of Potosi mountain.

There is no reason to doubt that the tin mineralization took place at approximately the same period throughout the entire district. Therefore, since most of the northern deposits (see Fig. 54) are just as clearly related in age to the crystalline granites as are most of the southern tin occurrences to their associated porphyries, it follows that the granite and the porphyries are of approximately the same age, the latter being an expression of the hypabyssal and volcanic conditions surrounding their solidification. The age correlation of these two types, rather than their absolute age, most concerns the present genetic theory of the origin of the tin veins, but if the porphyries were intruded in late Tertiary time, and this seems to be established, then the granite core and the elevation of the Cordillera Real of Bolivia must be of approximately the same age. This may seem startling in view of their long accepted Paleozoic origin, but the earlier geologists of the region based their age interpretations upon no more positive evidence than the fact that Silurian and Devonian sediments had been intruded by the granites. This proves only that they were post-Devonian. The youngest rocks intruded define the age, and in this case later discoveries have shown these to be late Tertiary. To be consistent, the intrusives may date anywhere from Pliocene to recent on this evidence, but deeply eroded late andesite flows in places cover the porphyries and their associated sedimentaries, and a considerable cover has been removed from the granite in the north, thus precluding the possibility of a recent age. The occurrence of wide spread igneous activity at the end of the Tertiary in other parts of the world is consistent with a similar age for the intrusions of this region.

[7] Op. cit.

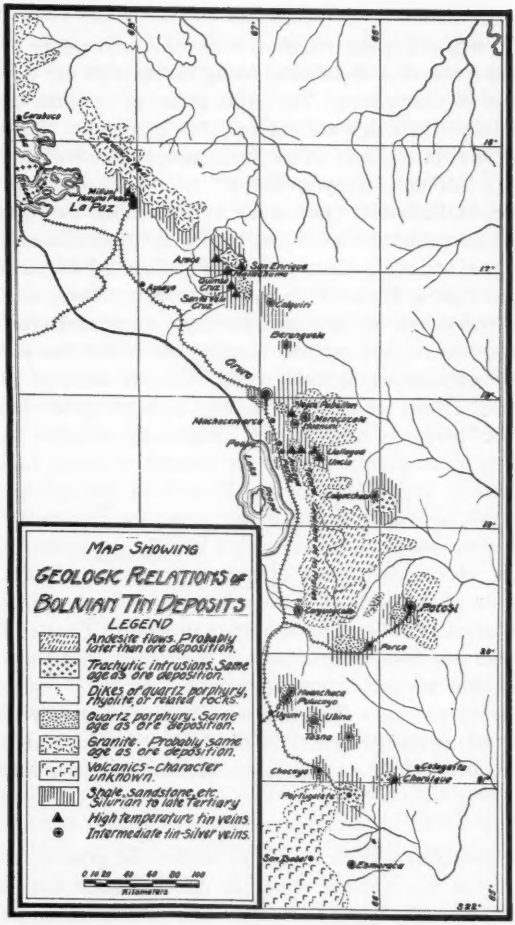



FIG. 54. Map showing geological relations of Bolivian Tin Deposits. Geology compiled from numerous reports on the mining districts, etc. Not drawn strictly to scale.

### THE VEINS.

Reference to Fig. 54 will show with what uniformity the mineralization has been distributed along the axis of the Cordillera Real and its extensions. The veins occur on both the east and west sides of the range and are found in granite, its related porphyries, and in any and all of the intruded sedimentaries. The mines of Milluni, Huayna Potosi, Araca, Choquetanga, San Enrique, Mallachuma, Quimsa Cruz, and Santa Vela Cruz are grouped along the west and south border of the granite area. All of the rest, including Oruro, Negro Pabellon, Llallagua, Uncia, Avicaya, Potosi, Porco, Pulacayo, and many others, are found in or about intrusions of quartz porphyry or related types, with the exception of one or two occurrences where the workings have not exposed the igneous rocks. Granite outcrops in small areas near Potosi and, of course, may be at no great depth beneath the surface in many places. Especially probable does the proximity of the granite seem in the vicinity of Uncia, Llallagua, and Avicaya, as indicated by the likeness of this group of deposits to those actually found in and about the granite itself.

The veins vary from fissure veins, usually not more than one meter in width, with filling of ore and gangue and with mineralization of the wall of greater or less extent, to mineralized breccia zones, sometimes many meters in width. Crusted fillings of cavities and banded structures in connection with them point to deposition in open fissures, but veins formed by replacement processes also occur. The fissures are usually steeply dipping breaks and shrinkage cracks in the igneous rocks and equally steep fractures along or across the bedding in the sedimentary rocks.

### MINERALIZATION.

*Tin-tourmaline.*—In veins found within the granite, as illustrated at the San Enrique mine, the mineralization has been of a distinctly simple type, tourmaline and cassiterite, in varying proportions, constituting practically all of the ore. This mineral composition is found in veins of other countries where the genetic relations to granitic rocks is clearly defined and where all factors

point to ore deposition under conditions of the high temperature zone. Moreover, at the San Enrique mine, the granite is apparently the only igneous rock present and it seems logical to apply the same reasoning which all investigators have used in genetically connecting the tin-silver veins to the south with the porphyries in which they are found. Thus the character of the including rock as well as the mineralization makes it impossible to assign to these veins any but a deep zone origin and they are here classed as the highest temperature facies among the tin deposits of the region.

Not far removed genetically from the veins within the granite are those just across the contact in the intruded sediments. At the Mallachuma mine, a few miles southwest of the San Enrique, the veins are in the sediments not far from the granite contact. (See Fig. 55.) Though abundant cassiterite and some

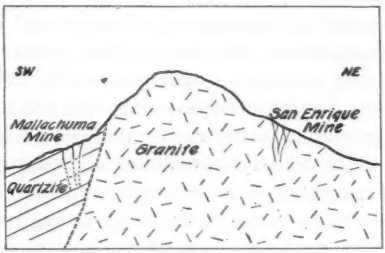



FIG. 55. Idealized section showing relations of veins to including rock at the San Enrique and Mallachuma mines.

tourmaline persist, the vein-filling includes pyrrhotite, pyrite, arsenopyrite, chalcopyrite, and quartz, all of which except pyrrhotite being common in other veins of the province which clearly formed under conditions of the intermediate vein zone. Here slightly lower temperature conditions must, of necessity, have prevailed and it is possible to trace the change in the character of the mineralization which paralleled the fall in temperature and pressure. Thus it is apparent that the mineralization here con-

firms the structural relations in indicating that ore deposition took place under temperatures and pressures slightly less intense than in the case of veins in the granite.

Araca, Milluni, Huayna Potosi, Quimsa Cruz, and Santa Vela Cruz are also in the sedimentaries, grouped about the granite at varying distances from the contact. There are differences in their characters which will be described in the section on the ores, but they range from typical high temperature veins with abundant tourmaline to somewhat lower temperature types with little or no tourmaline. None of these deposits could be classed as of the intermediate zone type, however, their relative nearness to the granite and their mineral content requiring higher temperature conditions.

More than one hundred miles southeast of the southern edge of the exposed granite are the deposits at Uncia, Llallagua, Avicaya, etc., grouped in an area of numerous porphyritic intrusions accompanied by intensive silicification and tourmalinization. The ores consist of massive cassiterite, pyrite, bismuthinite, and quartz, with abundant tourmaline locally. Some arsenopyrite is present, but other sulphides are rare and in small quantities. The mineralization is clearly that of the northern high temperature deposits, which, combined with the coarseness of much of the porphyry and the intensive impregnation of the material surrounding many of the veins, strongly points to ore deposition under conditions simulating those of the high temperature zone. This can be explained either by close proximity to the underlying granite core, which is entirely possible, or by supposing that numerous closely spaced intrusive masses of moderate size created conditions of temperature approaching those near a large plutonic body. These are in reality not two explanations, since both conditions might very likely co-exist. Certain it is that there is no factor in the occurrence of this group of high temperature tin veins which is not plausibly explained in accordance with the general genetic theory here developed.

*Tin-silver.*—Another class of deposits, characterized by quite different mineralization from the preceding, comprises the com-

plex sulphide ores associated with porphyries, and in some cases, volcanic igneous rocks. These deposits are in no place near granites or other plutonic rocks, and their structural and field relations entirely support the mineral evidence pointing to an origin under conditions of temperature and pressure likely to characterize the intermediate vein zone. Though cassiterite is common to all the tin veins, being found in most of the sulphide ores, minerals such as tourmaline, topaz, pyrrhotite, etc., are present only in very small amount in any except the high temperature deposits. Stannite, tetrahedrite, jamesonite, arsenopyrite, and some complex bismuth minerals are abundant in many of these intermediate veins, though absent or rare in the former type. Locally there are found complex sulphides of lead, tin, and antimony, such as cylindrite and related minerals, occurring in quantities sufficient to make a distinct type of ore. Silver is associated with all of the sulphide ores ,in the tetrahedrite chiefly, but also very widespread in the form of ruby silver which occurs in small amount with all the other sulphides, though it is everywhere very late and may be due entirely to supergene processes. Well crystallized quartz is the dominant gangue mineral throughout. These veins, as pointed out from the field relations, constitute a distinct class in which ore deposition took place at intermediate depths and temperatures.

*Silver.*—There is perhaps a third class of veins in the district, in which there is little or no tin. However, all information concerning many of these deposits, which include Pulacayo, Garguaycollo, Colquechaca, Portugalete, and others, dates back to the period before active tin mining in the district, when only the silver was exploited, and small quantities of tin may occur. Nevertheless, since they have not been reopened it is certain that their tin content is negligible as compared to that in deposits such as those at Potosi. Any explanation of these last occurrences must be founded upon a very incomplete knowledge of them, but since in the first two classes considered, predominant sulphides with increasing silver content marked the transition from high to intermediate temperature conditions, it is not unreasonable to

assume that the silver type, more or less free from tin, represents a stage of mineralization one step further removed from the source than that represented by the tin-silver vein. Support is lent to this suggestion by the volcanic texture of some of the associated igneous rocks. Dacites and rhyolites at Colquechaca and andesite at Portugalete are probably genetically related to the veins, and certainly solidified nearer to the surface and at lower temperature than did the rather coarse grained porphyries found with so many of the deposits previously considered. The minerals found in these silver districts are much the same as elsewhere in the tin-silver ores, with the exception of the tin minerals, and indicate a temperature of ore deposition probably still within the limits of what may be called the intermediate vein zone.

*Summary.*—Thus, to summarize the types of hypogene mineralization in the region, there are, chiefly in and about coarsely crystalline granite, veins characterized by a content of tin in the form of oxide, bismuth, some iron and copper sulphides, and minerals containing boron, fluorine, chlorine, etc. From this there are all gradations into veins in and surrounding quartz porphyry intrusions and characterized by tin, both as oxide and in complex sulphides, silver, chiefly in argentiferous tetrahedrite, and lead, copper, iron, bismuth, arsenic, and antimony in the form of sulpho-salts. This type passes in some instances into a more extreme case, associated partly with volcanic rocks, and in which tin is scarce or absent, but with other phases of the mineralization essentially the same.

*Enrichment.*—Supergene processes played a most important rôle during post-depositional periods in the silver bearing veins, where the most striking enrichment occurred. Oxidized silver minerals with abundant cerargyrite were worked near the surface by the Incas and later by the Spanish conquerors at Porco, Potosi, Oruro, and other places. These ores were followed in depth by large quantities of ruby silver, which, since it is comparatively rare in the still deeper portion of the veins now being worked, was very probably due to supergene deposition.

Tin has also been enriched, but the process has not been so clearly defined and simple as in the case of the silver. Removal of more soluble material from the upper portions of the cassiterite veins left oxidized ores, or *pacos,* rich in tin. Cases have also been described where the removal of the oxidizable material has permitted small grains of cassiterite to work downwards and become mechanically concentrated along the foot wall. There is no evidence of any supergene tin sulphides unless possibly the unknown mineral described on page 486 should prove to be a tin mineral.

Large quantities of "wood tin" occur in many of the upper workings, and while there is no positive evidence as to its source, the obviously oxidized character of the material in which it was invariably observed and its relative abundance in the uppermost portions of the deposits would seem to suggest a supergene origin. A thin section of ore near the surface from the Colorado mine, near Oruro, is illustrated in Plate XVI, *a.* Dark concretionary "wood-tin" has probably replaced both crystalline quartz and an early yellow cassiterite. The chemistry of this replacement is not clear, but a few suggestions follow from the relations observed. First, the fresh ores in the deposits where "wood-tin" is abundant contain large amounts of pyrite, and much limonite derived from this pyrite remains. This conclusively indicates that the surface waters which acted upon the material were acid solutions, necessitated by the hydrolysis of predominant ferric sulphate in them. Cassiterite is relatively insoluble in acid waters and consequently the source of the tin for the great quantities of "wood-tin" present could hardly have been the oxide. It is believed that stannite, which is more abundant than usually reported in the complex sulphide ores, was dissolved during the oxidation and supplied the necessary tin. Between this point and the precipitation of a colloid gel of metastannic acid from which the "wood-tin" probably crystallized we are in the realm of speculation. One fact, however, seems clear; quartz and cassiterite were readily dissolved by the solutions which deposited this secondary "wood-tin," two minerals notably insoluble in

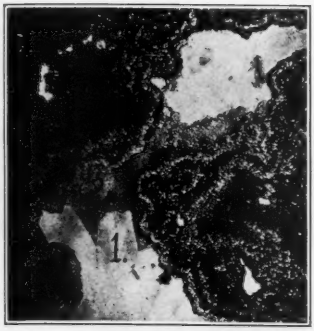
acid solutions. Therefore any explanation must account for a pronounced change from acidity to alkalinity in the tin-bearing solutions.

This might be explained by calling attention to the fact that the enrichment of tin was probably accompanied by a large scale enrichment of silver. The deposition of supergene silver sulphides has a reducing action upon the solutions, which, conceivably may not precipitate their tin during this change from acidity to alkalinity, but throw it down in colloidal form only at some later stage. Satisfactory treatment of this question is made difficult by the lack of experimental chemical work such as has been done in connection with the deposition of supergene minerals of the more common metals.

With the exception of the outbreak of hot waters in the mines at Pulacayo in 1895, none of the mines of the country appear, from the literature, to have encountered ground waters, and consequently, zones of oxidation, supergene sulphide enrichment, and hypogene deposition are all found above the water table.

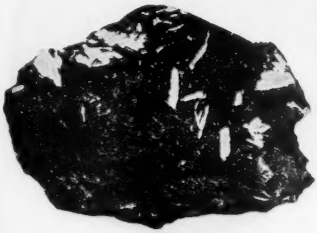
## THE ORES.

*Basis of Classification.*—In describing the ores found throughout the wide extent of the region no attempt is here made to cover each individual case. Practically every possible gradation exists between one type and another, but it is nevertheless true that there are certain associations of minerals which are repeated frequently enough to become characteristic and it is these distinct classes of ore that will be dealt with in some detail. Furthermore, as already pointed out, there is a distinct relation existing between the character of the ore and its association with and nearness to the genetically connected igneous rocks. Though this relation is not entirely simple, due to differing conditions with consequent differing ore types in neighboring veins, it nevertheless affords the most logical criteria for classifying the ores of the region, and, for descriptive purposes, major groups of the deposits are arranged accordingly. The subdivisions are based upon mineral composition and are represented by types

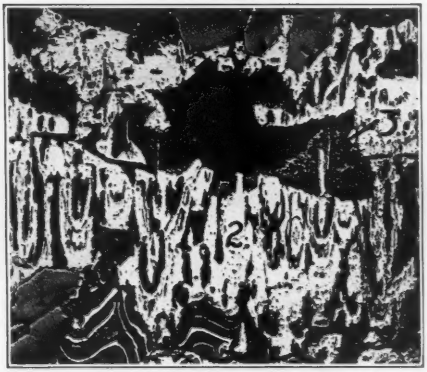



*a.*

*b.*



*c.*




*d.*

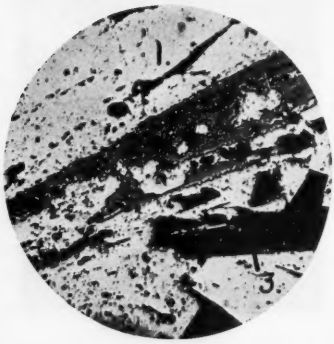
*a.* Pacos from Colorado Mine, near Oruro. 1, Crystalline quartz. 2, Yellow hypogene cassiterite. 3, Dark "wood-tin" probably replacing both 1 and 2. Thin section. × 10.

*b.* Hand specimen of ore from Carmen vein, Milluni. Native bismuth bordered by bismuthinite which appears striated across the vein. × ½.

*c.* Hand specimen of ore from Uncia consisting of dark cassiterite and bright crystals of bismuthinite. × ½.

*d.* Ore from 411 meter level on A–1 vein at Uncia. 1, Quartz. 2, Marcasite, showing longitudinal sections of stalatitic forms. 3, Gypsum. Polished section. × 15.

*a.*

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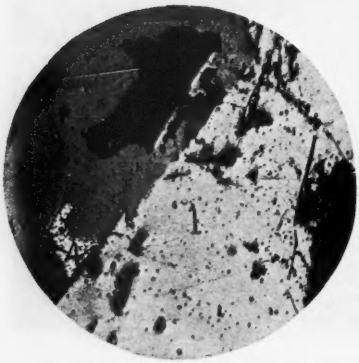


*c.*

*d.*

*a.* Pacos from Colorado Mine, near Oruro. 1, Quartz. 2, Yellow cassiterite showing zoning and twining. 3, Limonite. Thin section. × 7.5.

*b.* Band C, Fig. 56. 1, Arsenopyrite. 2, Stannite. 3, Angular cavities. Polished section. × 520.

*c.* Cylindrite ore. 1, Cylindrite. 2, Stannite. 3, Sphalerite. 4, Pyrite. Polished section. × 150.

*d.* Damasia Vein at Uncia, 411 meter level. 1, Native arsenic. 2, Realgar. 3, Gypsum. Polished section. × 15.

studied in the course of this examination. Certain groups of predominant minerals stand out and form the skeleton of the following description of the tin-silver ores.

Both thin sections and polished sections have been studied, and in the latter case, the procedure and scheme of identification of minerals used were those described in detail in the author's text.[8]

*Classification.*

I. Deposits of the High Temperature Vein Zone.
  *A.* Veins in Granite.
    1. Cassiterite, tourmaline (hematite, pyrite, and quartz).
  *B.* Veins in Invaded Rock Near Granite Contact.
    1. Cassiterite, pyrite, quartz, tourmaline.
    2. Cassiterite, bismuth, bismuthinite (tourmaline, quartz, pyrite).
  *C.* Veins in or Close to Porphyries Grading Toward Granitic Types.
    1. Cassiterite, pyrite, quartz, tourmaline.
    2. Cassiterite, bismuthinite, pyrite, quartz, tourmaline.

II. Deposits of the Intermediate Vein Zone.
  *A.* Veins in or Close to Porphyries Grading Toward Volcanic Types.
    1. Tetrahedrite, stannite, cassiterite, pyrite, arsenopyrite, jamesonite, quartz, etc.
    2. Cylindrite, franckeite, stannite, sphalerite, cassiterite, pyrite, proustite, quartz.
  *B.* Veins in Invaded Rock, but Genetically Related to Porphyry.
    1. Tetrahedrite, pyrite, sphalerite, chalcopyrite, galena, proustite (probably traces of cassiterite).
  *C.* Veins in Volcanic Rock.
    1. Tetrahedrite, pyrite, sphalerite, chalcopyrite, galena, proustite (probably traces of cassiterite).

[8] Davy, W. Myron and Farnham, C. Mason, Microscopic Examination of the Ore Minerals. McGraw-Hill Book Co., New York, 1920.

*Deposits of the High Temperature Vein Zone.*

*Veins in Granite.*—Ores of this type are represented in the veins at the San Enrique mine. A freshly broken specimen shows a dark compact material of which the most striking feature is the presence of many small radiating groups of tourmaline needles. Minute grains of dark cassiterite can be readily distinguished by the eye. Under the microscope the tourmaline is clearly earlier than the cassiterite, as the latter is seen to mold about and fill the interstitial space of the tourmaline aggregates. Thin plates of specular hematite are scattered sparingly throughout the tourmaline and have been partly corroded and replaced by it. The tourmaline in this deposit and in many of the Bolivian tin mines is very light in color in thin section. It appears either colorless, in which case pleochroism is almost absent, or light brown, with moderate pleochroism. In the radiating aggregates the centers are often dark green or brown with colorless needles about the outside. The clearly hypogene cassiterite in this and other localities is light yellow when seen in thin section and commonly shows zoning and twining structures (see Plate XVII, *a*).

The granite wall rock of the veins has been strongly altered by the mineralizing solutions with the formation of a type of greisen. Residual quartz grains are about the only unaltered constituents of the original rock. The biotite is largely changed to chlorite and the feldspars are entirely replaced by a mat of fine sericite and some green tourmaline needles. Scattered grains of cassiterite and topaz have also been introduced, probably by the mineralization solutions.

Though there is no direct evidence for the relation between these veins and the including granite, there are no other igneous rocks in the vicinity; other deposits high in tourmaline are grouped about the granite exposure, and the veins actually in the granite exhibit characteristics usually interpreted as of the high temperature zone to a more intense degree than do any of the others. No effort is made to define the time lapse between the crystallization of the granite and the formation of the veins, but the latter certainly originated while the including rock yet re-

tained much of its great heat content and during the final escape of a residual fluid high in the so-called "mineralizers," boron, fluorine, chlorine, etc. These veins and others included among those of the high temperature zone are as closely comparable to certain of the tin veins of other countries as is usually possible between ore deposits of widely separated regions. There is little doubt that had these occurrences received careful study at an early period the misconceptions concerning the Bolivian tin veins would never have received so widespread a circulation.

*Veins in Invaded Rock Near Granite Contact.*—Ores representing this type are somewhat variable in composition and include a number of deposits such as Araca, Mallachuma, Milluni, and Huayna Potosi, etc. They are all characterized by abundant cassiterite, more or less tourmaline, and absence of silver. Two types are to be distinguished, those containing cassiterite as the only valuable mineral, and those containing abundant bismuth. The former differs from the cassiterite-tourmaline veins in granite, only in the addition of more or less pyrite and quartz with sometimes very minor amounts of arsenopyrite, sphalerite, chalcopyrite, etc.

The high bismuth type is represented by the Carmen vein at Milluni and is an interesting occurrence in large quantities of minerals present in but minor amounts at most other places in the region. The bismuth concentration appears to be more a question of local richness in the metal of the mineralizing solutions rather than to controlling influences of temperature, pressure, or surrounding rocks, though the higher temperature conditions are most favorable.

The typical appearance of a freshly fractured specimen of ore from this mine is illustrated in Plate XVI, *b*. Such specimens show large masses of native bismuth, in all cases surrounded by a layer of the sulphide, bismuthinite. In places the bismuth appears to occur in stringers, each mass of the native metal being pinched out and connected to an adjoining mass by a thin veinlet. Occasional grains of cassiterite are to be seen in these specimens, but it occurs more abundantly in mixtures of very fine grained

cassiterite and bismuthinite so closely intergrown that the mixture looks to the eye to be nothing but sulphide. This grades into material consisting of compact brownish cassiterite, seen in thin section under the microscope to be mixed with abundant slender prisms of tourmaline. Thin films of bluish black "wood-tin" fill the fissures in oxidized material. Some specimens contain much pyrite, and others quartz, but seldom, if ever, was a specimen from this vein seen in which all of the foregoing minerals occurred closely associated.

*Veins in or Close to Porphyries Grading Toward Granitic Types.*—In this group are included those veins in porphyry which resemble the preceding deposits. They are found in regions of closely spaced, rather coarse grained porphyry intrusions which have been accompanied by intensive silification and tourmalinization, and the ore is characteristically that of the more northern high temperature veins associated with granite. At Avicaya, Uncia, Llallagua, Negro Pabellon, and several other neighboring localities are found representatives of this class. For descriptive purposes this class naturally falls into two divisions based on bismuth content.

At Avicaya are veins in porphyry with abundant cassiterite, pyrite, quartz, and tourmaline, and at Uncia and Llallagua in the same district occur similar ores with less tourmaline and occasional minor amounts of such sulphides as stannite, sphalerite, and chalcopyrite. In the Avicaya mines the material varies locally from nearly pure cassiterite to a mixture showing abundant cassiterite scattered through hard, compact quartz with some intermixed pyrite. The tourmaline seems to be most abundant as impregnations in the porphyry and in stringers close to the wall. Both the porphyry and the hard quartzite are penetrated by veinlets of tourmaline, pyrite, quartz, and cassiterite.

Thin sections from this locality show large quartz phenocrysts as the only recognizable original constituent of the porphyry. The results of mineralizing agencies are fine-grained silicification, tourmalinization, and pyritization. Very considerable amounts of topaz have been introduced. In places this altered porphyry has every appearance of a typical greisen.

All the material available came from the immediate vicinity of intense mineralization and, consequently, fresh porphyries were not seen, but Rumbold[9] describes an unmineralized porphyry from the Mina Mariana at Tres Cruzes which is apparently typical of many of the quartz porphyries of the region. The rock is porphyritic with a felsitic groundmass. The phenocrysts are orthoclase feldspars, quartz, and biotite. The feldspar is often altered to muscovite.

A hand specimen of a prominent type of ore from Uncia and Llallagua consists of a hard, compact mixture of cassiterite, quartz, and pyrite. Other specimens show well-crystallized quartz deposited in and about altered and brecciated porphyry and, in turn, encrusted with large cassiterite crystals. The cassiterite is not infrequently covered by a still later deposition of marcasite. The oxidation of the original pyrite in many of the upper ores of the above type has yielded a dark, hard, and porous-looking product which consists largely of cassiterite, quartz, and limonite.

A thin section of the altered porphyry mentioned in the foregoing paragraph shows it to consist of the usual corroded quartz phenocrysts, muscovite crystals partially replaced by cassiterite, and a fine-grained ground mass of quartz, tourmaline, and cassiterite.

An unusual and interesting occurrence was observed on the 411 meter level in the Uncia property on the A–1 vein. In the hand specimen the appearance is that of the common massive cassiterite, quartz, pyrite mixture. A polished section of this material is illustrated in Plate XVI, *d*. Crystallized quartz and pyrite are apparently the earliest formed minerals and are followed by crystalline cassiterite. Stannite, sphalerite, and bismuthinite are present as minor accessories. Following these were deposited mammillary incrustations of a mineral slightly less creamy in color and slightly softer than the normal pyrite, but similar in chemical behavior, though more rapidly attacked by nitric acid. This is believed to be a type of marcasite. These incrustations,

[9] *Op. cit.*

which are stalactitic in form, have a circular cross section, occur in all attitudes, and the plane of a single polished surface cuts sections at all angles to their axes though local groups are often parallel. If these were the result of descending solutions moving under the force of gravity, it is difficult to see why some tendency toward vertical attitudes of the forms is not present. In addition to these shapes, fish-tail twins similar to those of gypsum occur, as well as irregular crustifications about and between stalactitic individuals. Following this was deposited pyrite (marcasite?) of normal appearance which replaces the earlier stalactites along concentric bands and also irregularly in fine intergrowths. So intimately are the two mixed that they might have been considered as of simultaneous origin had not a case been observed in which the later pyrite isolated and engulfed the end of a stalactite whose continuation beyond the enclosed portion was clearly traceable. These two minerals also occur encrusting cassiterite in other portions of the mine and to the naked eye the mixture has the appearance of typical marcasite and there can be little doubt as to its supergene origin. The latest mineral present is gypsum which has been deposited in fractures cutting all of the other minerals, in vugs where these are present, and in minute cracks throughout the marcasite.

The second general class of ore of the high temperature type in porphyry is also represented at Uncia. This is commonly a black, massive cassiterite intergrown with numerous thin bladed prisms of bismuthinite, whose bright cleavage faces are very prominent on a freshly broken specimen (see Plate XVI, *c*). The amount of bismuthinite varies greatly and shoots rich in this mineral grade into ores of the previous type in which it is practically absent.

### *Deposits of the Intermediate Vein Zone.*

*Veins in or Close to Porphyries Grading Toward Volcanic Types.*—Here fall the complex sulphide ores high in silver such as those found at Potosi and Oruro. In much of the material now taken from these mines silver-bearing minerals are not

prominent in the hand specimens, a hard, gray, sometimes banded, mixture of quartz and pyrite being common. Closer inspection often reveals somewhat darker areas and streaks which are largely cassiterite. Many specimens of this kind, in spite of their hardness and seeming compactness are quite porous and contain innumerable vugs of all sizes. These are usually incrusted with crystalline quartz accompanied or followed by one or more sulphides. Where pyrite is very abundant much of it is in the form of perfect cubes in the quartz encrustation.

When the vugs are of larger size, very complete observations are possible with the naked eye, and have afforded much of the information concerning primary mineralization available in the past. One specimen examined from Oruro shows an early deposition of crystalline quartz and pyrite with minor amounts of cassiterite. This is followed by a continuous band of brownish cassiterite, in turn covered by an encrustation of crystalline quartz. Finally upon the surface of this encrustation are small amounts of stannite and tetrahedrite, with many matted groups of thin jamesonite or zinkenite needles. The deposition of tetrahedrite overlaps the period of deposition of the jamesonite as indicated by the penetration of many of the needles into the tetrahedrite crystals.

Much the same mineralization is seen in massive, compact sulphide mixtures containing only minor amounts of quartz. Pyrite, stannite, and a tetrahedrite high in silver (freibergite) are prominent as a rule. The stannite is much more commonly present than previous descriptions would indicate. Almost no sulphide ores from Potosi or Oruro were seen which did not show appreciable quantities of the mineral on polished sections. When associated with much sphalerite and chalcopyrite as at one locality near Oruro there is a very intimate intermixture of the three minerals. A polished section at low magnifications shows large, distinct grains of each, apparently homogeneous, but at the higher powers every grain is seen to contain very minute dots of the other two minerals. So abundant are sphalerite and chalcopyrite specks in the stannite that at one place it will have a distinctly grayish and at another a yellowish cast.

Tetrahedrite crystals often line vugs, but more commonly occur in massive mixtures. A bismuth sulphide with lead or silver is widely distributed throughout all of these ores, but in microscopic grains too minute to permit of exact identification. Where jamesonite is present it lines vugs and cavities and appears to be the latest mineral deposited by the hypogene solutions. Proustite and pyrargyrite are widely scattered as very late minerals, but the indications are that they are products of supergene processes in most cases at least.

A polished section of banded ore from the San Miguel vein at Potosi mountain is pictured in Fig. 56. This has been chosen for description in detail because it illustrates nicely a typical as-

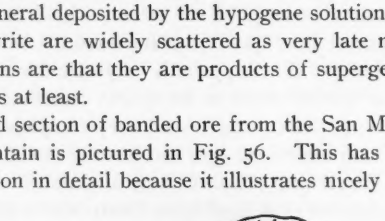


FIG. 56. Ore from San Miguel vein at Potosi Mountain. 1, Tetrahedrite. 2, Pyrite. 3, Quartz. 4, Arsenopyrite and pyrite. (See detailed description.) Polished section. Natural size.

sociation of minerals and presents evidence for replacement deposition of the vein filling in this case.

Band *C* is a mat of interlocked prismatic crystals of arsenopyrite accompanied by pyrite. The depositional periods of these minerals are clearly simultaneous, since in one instance arsenopyrite is molded about a pyrite crystal and in another the reverse relation is true. This band appears to be the first product of the mineralizing solutions and was formed in a narrow seam or fissure not more than a fraction of a centimeter in width.

This was followed by the introduction of solutions which deposited quartz primarily. This quartz filled interstitial spaces throughout band *C* and replaced the enclosing material on both

sides to form bands *B* and *D*. These consist of crystalline quartz so closely grown as to reveal evidence of crystal form only under the microscope and where a crystal terminates in a vug, in which case later stannite and tetrahedrite are molded about the quartz. Through these bands are scattered crystals of pyrite and some arsenopyrite, both as detached individuals and roughly banded. Thin sections reveal the presence of numerous small cassiterite grains and square sections of topaz. The closing facies of this mineralizing stage are seen in crystals of pyrite, arsenopyrite, and quartz linked together to form a skeleton throughout bands *A* and *E*.

The character of the solutions underwent a marked change. Such metals as copper, silver, and bismuth appear and the tin becomes stable as the sulphide, stannite, instead of the oxide, cassiterite. Stannite was the first of these sulphides to be deposited and it is seen replacing the interior of the arsenopyrite crystals and filling vugs in the early as well as later bands. The manner in which it attacks the arsenopyrite is illustrated in Plate XVII, *b*, from band *C*, where replacement takes place most readily parallel to the long dimension of the arsenopyrite crystal. The solutions next were impoverished in tin, but deposited abundant silver-bearing tetrahedrite (freibergite) which, with minor amounts of a bismuth sulphide with lead or silver (beegerite or matildite) constitutes the material of bands *A* and *E*.

The symmetrical arrangement of the banding on both sides of a central band which is clearly the earliest formed could hardly be explained on the basis of crustification in open fissures. This latter type of ore deposition is undoubtedly present in many cases and may well be the rule, but it is equally evident that replacement veins are not entirely absent. The sequence of mineral formation as seen in the case just described and made more comprehensive by the study of many other cases is graphically shown in Fig. 57.

A class of ore containing abundant cylindrite and heretofore undescribed except as a mineral curiosity has in recent years been discovered in sufficient amount to justify special ore dress-

ing tests for milling it. The exact locality of the material described is, however, unknown. In appearance it is distinctly different from any other tin ores of the country. A specimen of typical high grade material is a compact, lead-gray mixture of sulphides which are soft and dirty the hands. Oftentimes the cylindrical shells into which cylindrite characteristically cleaves are prominent on a broken face of ore. In other cases good prismatic cleavage points to the presence of franckeite. Occasionally large amounts of sphalerite are to be distinguished intergrown with the other minerals.

Polished sections of these ores show that practically all the minerals present in the previously described sulphide ores occur in lesser amounts in this type and in the same general relation. The cylindrite and franckeite are in all cases related to the earlier period of ore deposition, being distinctly older than the stannite, sphalerite, and late pyrite with which it is most commonly associated. Plate XVII, *c*, pictures the border of an area of cylindrite against which these minerals have been deposited with a sharp, straight (really a circular arc of long radius) contact. Considerable chalcopyrite is present, traces of tetrahedrite are sparsely scattered, and much proustite and possibly others of the ruby silvers are present. As elsewhere, these are of very late origin, possibly supergene, but in this case there is no other apparent source of the hypogene silver content and these sulpho-salts of silver may have to be placed with the latest phase of hypogene deposition.

There is one mineral occurring abundantly in many ores of this type which has not been identified and which may possibly be of great interest in connection with the question of supergene enrichment of tin. It occurs in very fine veinlets cutting and replacing cylindrite chiefly, but other minerals to some extent. It is clearly the latest mineral formed wherever seen and no hesitancy is felt in ascribing it to supergene processes. On a polished section is has about the color of sphalerite (gray), is slightly harder, possibly has a light streak (?), but is absolutely opaque in thin section. It effervesces and darkens when treated with

nitric acid. No mineral known to the writer agrees with it in properties and it is so finely divided and intimately mixed with cylindrite that nothing but the finest microscopic grains can be separated with a needle and these cannot confidently be depended upon as free of contamination. No reliable tests can be made upon such material, but as far as could be detected it shows no constituents foreign to cylindrite. The latter being a sulph-antimonide of lead and tin, the relations suggest the probability that the unknown may be a compound of one of these metals. Its hardness, appearance, and microchemical behavior bear no resemblance to any lead or antimony minerals and it seems altogether possible that a natural sulphide of tin or some other unknown tin mineral is here present. It is to be hoped that the future will yield an occurrence of this mineral in grains of a size permitting more ready identification.

*Veins in Invaded Rock, but Genetically Related to Porphyry.*—This group is not clearly defined in veins studied by the writer, but it is apparent from descriptions in the literature of some of the southern deposits high in silver and containing little or no tin that such a division in the classification should be made. These veins contain practically the same sulphides as are found in the preceding descriptions of silver-tin ores with the exception of those containing tin, and these latter must even be present to a limited extent in some cases since in recent years small tin productions have been credited to districts heretofore considered to contain silver deposits only.

A small scale illustration of this change of character in the ore when passing from the porphyries into surrounding sedimentaries is found in the Rasgo vein at Oruro. Where in the porphyry the vein contains pyrite, cassiterite, stannite, tetrahedrite, etc., in the invaded slates it splits into narrow, non-persistent stringers practically free of tin and rich in silver. In other places such a change is not so marked, especially where well-defined fractures pass from the igneous into the adjoining rocks.

*Veins in Volcanic Rock.*—This and the foregoing veins were apparently formed at the lowest temperature of any related to

the silver-tin deposits. Colquechaca, Portugalete, Chocaya, and Chorolque are examples of this type, the veins occurring in rhyolites, trachytes, dacites, and andesites according to the descriptions available. While silver is the only metal of economic importance, as stated before, recent small tin productions relate these deposits genetically to the tin-silver mineralization. Their mineralogy is largely that of the other deposits described, with the tin minerals probably present in minor amounts. This information is necessarily from older literature, since no modern reports are available and no ore specimens from these districts are in the collections gathered for this examination.

*Some Supergene Products.*

Two mineralogically interesting occurrences of secondary antimony and arsenic were observed and are briefly described at this point.

Thin, mammillary incrustations of a purplish gray, massive substance locally termed "kermesita" are found on the walls of open fissures in the mines of Oruro about 200 meters below the surface. The mineral has a brilliant red streak, conchoidal fracture, and in the closed tube its behavior is identical with that of stibnite. No trace of the small amount of oxygen present in kermesite was detectable in this mineral by blowpipe methods. Material carefully examined on a polished section and seen to be free of any impurity except small amounts of antimony ocher was analyzed for sulphur. Two determinations gave 25.8 per cent. and 26.3 per cent. respectively. Since kermesite contains but 20.0 per cent. of sulphur and stibnite 28.6 per cent. it is evident that the material in question conforms to stibnite in composition. It is slightly translucent in very thin splinters, showing brilliant red color in polarized light, and is doubly refracting between crossed nicols, but is cryptocrystalline, thus preventing the determination of other optical properties. It is believed that the mineral is the red antimony trisulphide, meta-stibnite,[10] heretofore undescribed from ore deposits.

[10] G. F. Becker, U. S. G. S. Mon. XIII, pp. 343–389, 1888.

Another interesting and somewhat similar case is the occurrence of realgar and native arsenic in the Damasia vein at Uncia on the 411 meter level. Layers of a mixture of these two minerals with small gypsum plates have been deposited one upon the other. Plate XVII, *d* illustrates the appearance of a polished section of the material. Arsenic is so often said to be dissipated in the oxidation of ore deposits that its appearance here in considerable quantity as a supergene mineral is noted. The material has all the appearance of a dark limonite, giving little suggestion to the naked eye of the orange color of realgar. Very small amounts of covellite have been deposited upon the surface of these oxidation products.

### ALTERATION OF THE WALL ROCK.

The nicely defined changes in the character of the vein fillings paralleling changes in temperature and pressure conditions are not nearly so evident in the alteration of the wall rocks. The same general types of metasomatic replacement of the including rocks characterize practically all of the deposits classed as high temperature veins and to a less pronounced degree even many of those of the intermediate vein zone.

In both the granites and porphyries from near the veins there are invariably seen residual quartz phenocrysts, usually corroded to rounded shapes, accompanied and often surrounded by masses of fine-grained secondary quartz. Biotite has given place to chlorite and rarely to large muscovite crystals. Feldspars have been completely replaced by mats of fine grained tourmaline, cassiterite, and very rarely sericite. The total absence of even the slightest traces of any feldspar is most striking. Nearly square or rectangular sections of topaz and some apatite grains are locally abundant as the earliest products of the mineralizing solutions. Tourmaline in small colorless and green needles and in large rosettes is later than the growth of fine-grained quartz, but earlier than the ever present cassiterite and the occasional grain or veinlet of pyrite.

In the actual vein filling quartz appears to have been deposited

later than tourmaline and even the earliest pyrite, consequently its formation in the wall rock in the first stage of metasomatic alteration seems contradictory. However, very early topaz and apatite indicate that the mineralizing agencies were high in fluorine and its compounds. These readily attack quartz, dissolving it from the phenocrysts and groundmass of the original porphyry or granite. The rapidly changing character of the solvents probably caused them to deposit their silica as fine grained quartz not far from the point of solution. This explanation of the origin of the quartz in the altered wall rocks is supported by the fact that analyses of fresh rock and of greisen from other districts point to little change in the silica content, thus precluding the probability of the addition of appreciable silica in this type of alteration.

The intensive silicification observed at some localities would seem to indicate that in those cases silica had been added, but the porous character of many such rocks makes it necessary to question if there has been an actual increase of silica per unit volume. In cases where a compact silicious rock has resulted much of the quartz is of the same age as that in the vein filling.

In deposits such as those at Potosi and many near Oruro which are classed in the intermediate vein zone the altered rocks show occasional minute grains of tourmaline and possibly topaz when examined in thin sections, thus tending to place such deposits toward the high temperature end of the intermediate zone.

Certain mineralogical alterations are so pronounced that they justify a few observations as to the chemical changes involved, which, however, can only be roughly indicated without analyses. There has in most cases been a leaching of sodium and potassium and also calcium. Boron, fluorine, tin, and possibly iron have been introduced. Alumina and silica are in this case considered as approximately constant.

### THE PARAGENESIS OF MINERALS.

A particular effort has been made to determine a clearly defined general sequence of mineral deposition for the Bolivian

tin-silver district, since in this way we may best arrive at an understanding of the changes that take place in the character of the mineralizing solutions. The microscopic examination of the massive mixed ores in polished sections has enabled more intimate studies of these mineral relations to be made than was heretofore possible. In Fig. 57 is given the sequence of the more abundant minerals, the thickest portion of each line representing the period of maximum deposition of the mineral.

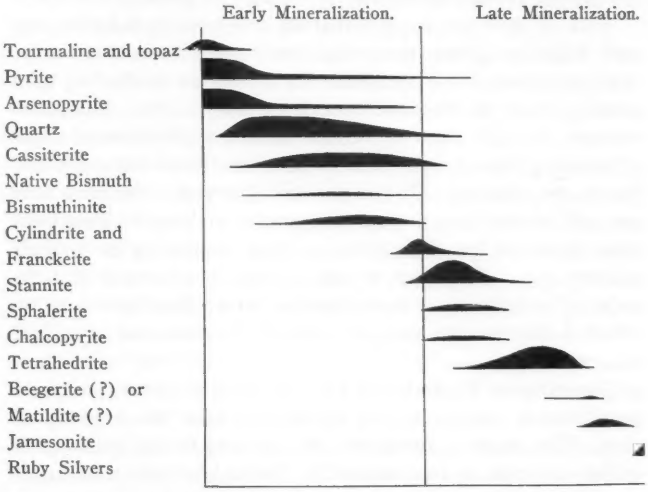


FIG. 57. Sequence of Mineral Deposition in the Bolivian Tin-Silver Deposits.

It is not possible to give a sharply cut sequence such as could be represented by a list of names in order, where each mineral is shown as forming only after the cessation of formation of a preceding one, because the various periods of deposition clearly overlap. Distinctly banded specimens often show one or two minerals such as quartz and pyrite persisting throughout several bands, with a different group of associated minerals in each band. In such cases there can be no question but that the period

of deposition of such quartz and pyrite overlaps that of several of the associated minerals. However, any one band examined microscopically will show an apparent order of crystallization within the band. The quartz may be molded about pyrite crystals and therefore appear to be deposited later, though both may be present in the following layer. Other minerals in any one band may be molded against crystal forms of both quartz and pyrite, therefore appearing later, but in the following layer they are absent, though quartz and pyrite may be present.

Such occurrences suggest that an ore-forming solution may and does precipitate more than one mineral simultaneously. Any one mineral will precipitate out as long as the feeding solutions contain its constituents and as long as the equilibrium changes, brought about by various factors, at the locus of deposition are sufficient to depress its solubility below its concentration in the solution. Of two minerals forming at the same time one will usually have a more pronounced tendency to assume its own crystal shape, thus giving a false impression as to their relative ages. Moreover, it must be kept in mind that it is the order of completion of crystallization rather than the beginning which determines the apparent relations between two associated minerals.

The sequence illustrated in Fig. 57 is not intended to express conditions as seen in any one specimen or even in one group of ores. The range of formation of a mineral in any specimen is seldom as great as represented for the region, for the arrangement of the diagram seeks to cover every type of occurrence seen in the various ores studied.

In every specimen in which tourmaline or topaz were present they were distinctly the first minerals introduced. Pyrite and arsenopyrite are the earliest of the common ore minerals and are always seen in well-defined crystals wherever they occur in this relation. Where banding or crustification are present they occur abundantly in the earliest bands. The solutions, however, were not always exhausted in these constituents in an early stage for in one specimen illustrated in Plate XVII, *c*, pyrite with stan-

nite and sphalerite is distinctly later than cylindrite, and Dr. L. J. Spencer describes a specimen consisting of an aggregate of jamesonite needles encrusted with small crystals of pyrite and stannite. This latter relation, however, is so contradictory to all occurrences seen by the writer that it is felt to be entirely exceptional, due to some unusual repetition of solutions.

Quartz always appears a little later than the earliest generation of pyrite and is usually very closely followed by cassiterite, which molds about the quartz crystals (Plate XVI, *a*), but assumes crystalline shapes on the walls of cavities.

In those ores which contain bismuth and its sulphide, bismuthinite, these minerals and cassiterite often seem nearly the same age, though an occasional specimen shows bismuthinite in layers surrounding native bismuth.

In the cylindrite ($Pb_6Sb_2Sn_6S_{21}$) and franckeite ($Pb_3Sb_2Sn_2S_{12}$) ores examined, these minerals were invariably earlier than any associated minerals except quartz and cassiterite. Hintze, in his mineralogy, quotes Frenzel as describing cylindrite grouped upon tetrahedrite ore from the Mina Pizarra at Oruro, but it is not clear whether he intends to give the impression that the tetrahedrite is the earlier.

Stannite, $SnCu_2FeS_4$, is present more or less abundantly in all the complex tin ores and is most commonly associated with tetrahedrite and with sphalerite and chalcopyrite. It is practically contemporaneous with the latter two, often occurring in very fine grained mixtures. The relation between the stannite and tetrahedrite is not always clear in the massive ores, but after studying some twenty different ores containing these minerals, the writer has come to the conclusion that stannite is usually the earlier. It commonly appears filling angles between the older minerals, all being surrounded by tetrahedrite, consistently giving the impression that the stannite areas are residual. In the specimen pictured in Fig. 56 the stannite occurs almost entirely in an earlier formed band than those which consist largely of tetrahedrite. Many specimens of massive ore show the two minerals apparently contemporaneous, but the writer has failed to

find any case in which stannite is later than tetrahedrite. However, Spencer[11] describes a specimen from the Socavon de la Virgen at Oruro which consists of a group of bright tetrahedrite crystals on a matrix of massive pyrite. Stannite crystals are plentifully scattered over the tetrahedrite, in the surface of which they are partly embedded. Thus it is seen that, though the majority of cases show the stannite slightly earlier than the tetrahedrite, their periods of deposition distinctly overlap and even the reverse of the common relation occurs.

Jamesonite, which is abundant in many of the sulphide ores, was observed in every case to be the last hypogene mineral formed, with the exception of pyrargyrite or proustite, which, though often supergene, are sometimes probably of late hypogene origin. The jamesonite needles encrust cavities in massive ores consisting of all the earlier minerals, including stannite and tetrahedrite. Its late origin is so clear cut in every instance that the case, described by Spencer, of jamesonite needles encrusted with pyrite and stannite requires an exceptional explanation. The gap to be bridged by an overlap in the periods of mineralization in this instance is too great and no attempt is made to fit the case into the normal sequence.

Germanium, a rare metal whose minerals are curiosities of the Bolivian tin ores, was unobserved by the writer, though even microscopic occurrences were searched for. This is not surprising since the material studied was chosen as typical ore rather than as mineralogical specimens. It is interesting to note, however, that at least one of the germanium minerals, argyrodite, $Ag_6GeS_5$, is of very late origin. Prior and Spencer[12] describe a specimen from Colquehaca on which numerous small, dull black, cubic crystals of stanniferous argyrodite encrust pyrargyrite, as a later growth.

## MAGMATIC DIFFERENTIATION.

Connected with the great body of acidic magma whose injection accompanied the elevation of these great ranges were quan-

[11] L. J. Spencer, *Mineralogical Mag.*, vol. 14, pp. 308–347, London, 1907.
[12] Prior, G. T. and Spencer, L. J., *Mineralogical Mag.*, vol. 12, p. 6, London.

tities of tin, silver, bismuth, copper, lead, zinc, iron, and antimony, with lesser amounts of gold, tungsten, arsenic, and the rare element germanium. Whatever there is unusual in this association of metals must be sought at this point. Some stage in the separation of this great fraction from its magmatic source has concentrated with it these metallic constituents. Though we are in the field of speculation when we attempt to explain this concentration and separation, in other words, the basic processes of differentiation, we can at least safely draw comparisons and observe that granitic magmas the world over quite commonly carry this same association of metallic constituents with the exception of the silver and the germanium, a negligible accessory. Thus it seems that tin, tungsten, and bismuth, with varying amounts of the more common metallic elements, separate with acidic fractions just as magnetite and ilmenite, and in some places the metals of the platinum group often accompany the most basic fractions in magmatic differentiation.

Silver is a persistent and common metal, but its occurrences indicate that it does not normally appear with either of these differentiated extremes when given the opportunity to find a more stable environment. However, no one who has followed the developments of the last few years in our ideas concerning the history of igneous rocks would reasonably expect the same sequence of steps to be duplicated in all cases. That some disturbance might prematurely squeeze off a portion of the magma still molten at any stage in the process of differentiation, and with it constituents which would have separated with other portions had the process not been interrupted, is entirely conceivable. Among these may be the silver of this case or the additional proportion of rock-forming constituents which serve to distinguish a rock in one locality from a closely allied example in another region.

At any rate, these considerations go farther behind the scenes than is apt to be productive of useful results when examining into the origin of ore deposits at the present state of our knowl-

edge. We must begin with a magma containing certain constituents and determine what conditions and what processes are favorable to the formation of ores, and further, in what way and to what extent the character of the ore will be influenced by these conditions and processes. By the solution of these problems do we attain a more intelligent and productive development of the world's present ore bodies, and greater facility in discovering new seats of mineralization when we have exhausted those resources which betray their presence at the surface.

### FUTURE OF TIN MINING IN THE COUNTRY.

In spite of the great wealth in metals taken in the last few hundred years from this, one of the world's richest mineralized regions, there seems no prospect of a decline for many years to come. So difficult is the country that, in spite of the natural prospecting ability of the natives and Spaniards, who have combed the country for centuries, new veins are not infrequently located. Inspection of the map, Fig. 54, would seem to encourage prospecting along the eastern contact of the granite core in the north, where deposits of the high temperature cassiterite type may be expected in accordance with the genetic theories developed in this paper. The large areas covered by late volcanic flows east of Negro Pabellon, Huanuni, etc., and east and north of Garguaycollo seem to be the least promising fields for new discoveries, for if the present age interpretation of these flows is correct, the chances of a deposit coinciding with any small area, from which the late cover may be eroded, is small. It is most likely, as has been suggested by other writers, that many valuable deposits may be covered by these flows.

Recent announcements that large American mining interests have bought up extensive holdings in the country point to a day soon to come when thoroughly modern methods of mining and milling will place Bolivian tin production upon a footing commensurate with the richness of the districts.

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# THE PALANGANA SALT DOME, DUVAL COUNTY, TEXAS.[1]

DONALD C. BARTON.

## INTRODUCTION.

Palangana is one of the more newly discovered salt domes of the Texas Gulf Coast. The basin-like depression from which it derives its Spanish name of "Washbasin" has long been known. The early settlers were attracted to camp there because of the presence of one of the rare ponds of the region. The pond, however, is now dry. Palangana is without oil or gas seeps, paraffine dirt, mineral springs, or surficial dome, and so until within the last few years its character passed unrecognized. Attention was finally drawn to it through its proximity to the old shallow field on the Piedras Pintas Salt dome. The Sinclair Oil and Refining Company finally drilled it and by going into salt proved its salt dome character.

## LOCATION.

Palangana is in southern Texas, in the east central part of Duval County. (See Fig. 58.) It is about 110 miles due south of San Antonio, and about half way between Laredo and Corpus Christi and a little north of the line connecting those two points. It is best reached from San Diego, from which it lies 15 miles west, or from the small town of Benavides, from which it is 6 miles north. Both points are on the Texas Mexican Railroad. Palangana is four miles north-northwest of the old shallow oil field of the Piedras Pintas salt dome.

## PHYSIOGRAPHY.

Palangana lies in the Gulf Costal Plain, on the edge of a cuesta which is upheld by a phase of the Reynosa. From the

[1] Published by permission of the Amerada Petroleum Corporation.

crest of the cuesta, there is a gently rolling upland surface sloping faintly eastward. Within the general vicinity of Palangana, it is deeply incised by San Diego Creek, Taranchua Creek, and Santa Gertrudis Creek, and their tributaries, but further to the eastward becomes flatly rolling with shallow valleys. West of the cuesta, there is a gently rolling region of low, rounded hills

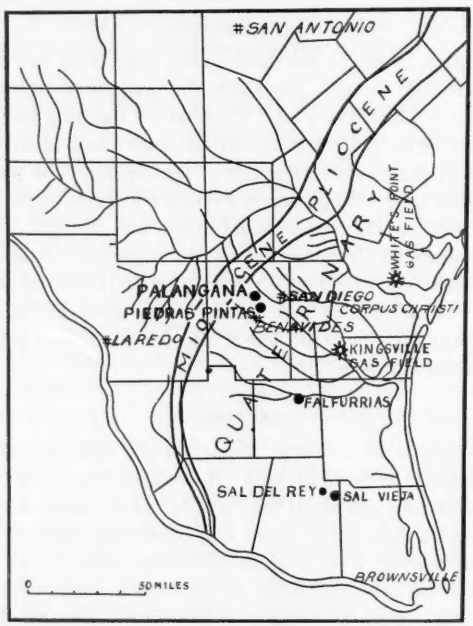


FIG. 58. Sketch map showing location of Palangana salt dome.

and shallow valleys. The general elevation of the crest of the cuesta is 500 feet. That of the hill tops of the lower lands to the west is around 400 feet, and that of the valley bottoms is around 350–375 feet. The cuesta scarp comes in from the southwest, and south of Benavides bends eastward and becomes the

south scarp of the Santa Gertrudis valley. A mile east of Noleda, the scarp on the north of the valley bends to the north to become the cuesta scarp and takes a northwesterly course, concave around the Piedras Pintas Salt Dome and convex around Palangana.

The surficial expression of the Palangana salt dome is a circular ring of low hills surrounding a central, circular basin. The diameter of the floor of the basin is 8,000 feet. The diameter of the ring of hills, from crest to crest, is 15,000 feet. The crests rise 50–80 feet above the floor of the basin. On the East and the West, the hills of this circular rim slope rather quickly down to the level of the western lowlands. On the northwest, north, and east, they are separated from the uplands of the crest of the cuesta by a partial ring of valleys concentric with themselves and the central basin. On the northeast they slope quickly down into the valley of the Taranchua. They are broad flat-topped hills which rise to the general level, or slightly below it, of the upland of the cuesta crest. The floor of the basin is not a simple plain but is divided on a north south line through the center by a pair of low, shallow ridges. The basin is drained by a valley which breaches the rim on the southwest and empties into Piedras Pintas Creek.

There are three hypotheses that can be brought to explain the present surficial expression of Palangana.

1. That it is essentially the result of the warping of the present general land surface.

2. That it is the result of differential erosion of beds already having a domed structure.

3. That the central basin is due to collapse of the surface consequent upon the solution of the top of the salt core. This thesis is not a third alternative, but a modification of either of the two preceding hypotheses.

The evidence favors the second hypothesis in preference to the first. The crests of the ring of hills around the basin are broad and flat-topped and except where very evidently lowered by erosion, rise to the plane of the general level of the upland

surface to the northwest and the east. From the Empire Gas and Fuel Company's Palangana No. 1 well eastward there is a drop in 6,000 feet of only five feet. From the northwest crest northwestward there is in the same distance no drop and in a slightly greater distance there is a slight rise. The flat-topped

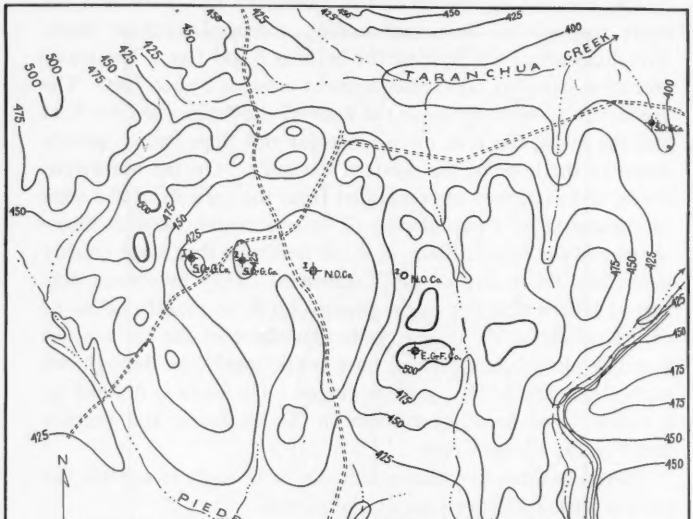


FIG. 59. Topographic map of the Palangana salt dome.

surface of the crests of the rim furthermore is separated from the upland surface by valleys which give every evidence of being erosional. This flat-topped surface of the rim would seem to be a remnant of the general upland surface. A doming of that surface of a magnitude of 10–15 feet, a magnitude which is only slightly less than that of the doming of the surface over such

salt domes as Hockley and Hull and greater than that over the salt domes at Pierce Junction and North Dayton, might, however, be extremely difficult, if not impossible, of detection on account of the very considerable dissection of this region.

In the salt domes of the coastal district that have thus far been studied by the writer, the surficial dome present is the result of warping of essentially the present surface, and the foot of the dome coincides in position, or lies within the projection on the surface of the periphery of the salt core and cap. But in the case of Palangana, the Empire Gas and Fuel Company's Palangana drill hole No. 1 shows that on the southeast at least, the crest of the ring of hills lies outside of the outer edge of the salt core and the cap, and thus suggests that these hills mark the edges of the faintly upturned lateral beds.

Several explanations could be formulated to explain the formation of the central basin. The explanation which might be offered, namely, that it was formed, as the writer suspects that the Vinton basin may have been formed, by the relatively greater uplift of the surrounding ridge and not by a negative movement of the basin, does not seem plausible for reasons which have been discussed in the preceding paragraphs. The probable origin seems to have been by normal erosion, or by slumping consequent upon the solution of the top of the salt core. The first explanation seems more satisfactory than the second. There is no indication of faulting around the periphery of the basin. The small spur ridges that project into the basin slope gently down from the inner slope of the rim with no break of slope to indicate the presence of a fault line. None of the three wells drilled within the basin encountered the heavy rock which caps the rim and which should be found over the basin if the latter were formed by down faulting. In the eastern half of the basin there is a single depression contour marking a closed depression of less than five feet. This depression may have to be explained by a negative movement due to solution or settling, or it may possibly be explainable by a positive movement of the enclosing barrier due to the hydration of the cap below from anhydrite to gypsum.

Except for this shallow depression, the central basin is drained through the valley which breaches the southwest quadrant of the rim. Erosion through this valley would seem competent to explain the origin of the central basin.[2]

SURFACE GEOLOGY.

Palangana lies in the belt that is mapped as Reynosa, and that formation forms the surface rock of most of the area. It is overlain in places by the Equus Beds, and locally the Lagarto Beds of the Miocene-Pliocene are exposed beneath it. The Reynosa, according to Dumble[3] usually is at the base a conglomerate with pebbles of different materials in a limy matrix. It is often indurated; in some cases tufaceous, sandy, or clayey. Above this continues a series of interbedded clays, limy sands, and sandstones with occasional pebbles, which may be identical with the Lagarto beds. The whole is capped by the Reynosa Limestone which most commonly is a tufaceous lime-rock but in places is so mixed with clay and sand as to lose that character. The Lagarto Beds consist mostly of sands and clays, but change to calcareous sand rock and in places siliceous or limy conglomerate. Below the Lagarto is the Lapara, which consists of sands and clays interbedded and cross-bedded and locally carrying porcelaneous and flintlike quartzitic material.

In the area immediately around Palangana, the conglomeratic phase is well exposed several miles to the east of the dome on the main road to San Diego. It was not seen at the dome. The intermediate series of clays and limy sands was not recognized at the dome. The limestone is much in evidence and forms the

[2] Since this discussion was written, information has been received that the National Oil Co.'s No. 2 Schallert encountered at 265 feet very hard siliceous beds that seemed to be dipping steeply toward the center of the dome. If this dip is that of the stratification, it would indicate that the central basin is the result of solution of the salt with the consequent slumping of the overlying beds. These beds are the result of silicification by thermal waters. It is very possible that the beds mark the upward course of these waters and not the stratification.

[3] Dumble, E. T.: Geol., of Southwest Texas, *Trans. A. I. M. E.*, October, 1902.

capping of the hills of the rim around the dome and of the edge of the plateau. This limestone, especially in the way it follows the surface slopes, exhibits some of the aspects of caliche. In Taranchua Creek, Dumble found sands underlying the Reynosa which he thought might be the Lagarto Beds. There is much sand in the central basin of Palangana which may correspond with those beds. But the correlation of the sandy beds of the central basin on the strength of lithological character alone without the evidence of fossils is dubious since there is the very real possibility that beds normally deep lying have been brought to the surface, as in the case of Keechi, Palestine, and West Point. Porcelaneous and flint-like quartzitic material similar to that described by Dumble as occurring in the Lapara to the west, outcrop on Piedras Pintas and on Palangana, the National Oil Co.'s No. 2 encountered a similar flinty quartzitic rock at a depth of 60 feet and again at 265 feet.

## SUB-SURFACE GEOLOGY.

A salt dome characteristically consists of a plug or core of rock salt, a thimble like cap of limestone, anhydrite, of gypsum mantling the salt core, and steep quaquaversally dipping beds around the salt core. The latter is circular or elliptical in plan with a diameter, of about half a mile as in the case of Anse la Butte, to three and one half miles by one and one half in the case of Stratton Ridge. The salt has nearly vertical sides and a relatively flat top. The flatness, however, is relative and there may be fairly steep slopes to the top of the salt. The cap may be hundreds of feet thick, or it may be practically absent, or thin on top and thick on the sides. The dip of the beds on the flanks of the dome varies with the dome and with the depth of the bed. It is in many cases around 1 in 1 but is less for the shallower beds and probably greater near the edge of the salt.

Although only four wells have been drilled on Palangana, they are so situated that it is possible to obtain a fair conception of the probable structure of the dome, and to recognize that it is that characteristic of a salt dome. Three of the wells have gone

into the salt. The Sinclair Oil and Gas Co.'s Schallert Nos. 1 and 2 both struck the salt at a depth of 845 feet (420 feet below sea level) and drilled 215 feet into the salt. The National Oil Co.'s Schallert No. 1 struck the salt at a depth of 985 feet (575 feet below sea level) and drilled 98 feet into the salt. The western part of the top of the salt is therefore flat. Across the center of the dome on an east west section there is a dip eastward of 1 in 15 to the National No. 1, and as the Empire Gas and Fuel Co.'s Palangana No. 1 had not encountered the salt or dome

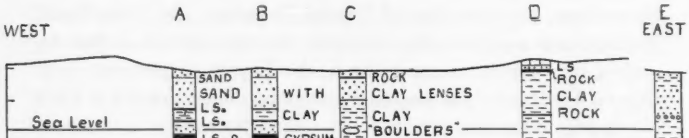


FIG. 60. East-west cross-section of the Palangana salt dome. *A*, Sinclair Oil and Gas Co.'s Schallert No. 1. *B*, Sinclair Oil and Gas Co.'s Schallert No. 2. *C*, National Oil Co.'s Schallert No. 1. *D*, Empire Gas and Fuel Co.'s Palangana No. 1. *E*, Sinclair Oil and Gas Co.'s Gravis No. 1.

materials at 3,000 feet (2,494 feet below sea level) there is a dip between those two wells of over 1 in 3. The probability is that there is no simple uniform slope between these two wells,

but rather (see Fig. 60) there is a slope of 1 in 15 or 13 for a distance, and then a rapid change of slope to almost vertical. West of the western salt well, the Sinclair Schallert No. 1, the flat top of the salt probably becomes steeper and finally nearly vertical, as on the southeast. To the north and the south there is probably a slope similar to that to the southeast but the vertical position is assumed in less distance. The top of the salt, however, may be very irregular and it is not safe to extrapolate too far from the known data.

The position of the edge of the salt is of the utmost importance in the development of a salt dome, as it limits the inner extension of the lateral sands. It must not be conceived of as a sharp line. It is irregular and, because of the fact that the slope is steep rather than vertical, it varies somewhat with depth. In some places, as may possibly be the case on the eastern side, a relatively shallow lateral sand might be continuous with a sand above the cap. At Palangana, the position of the edge of the salt has not been well defined. It has been limited on the southeast by the Empire Gas and Fuel Co.'s Palangana No. 1 which shows that the salt does not extend as far out as the crest of the ring of hills surrounding the central basin. The Sinclair Oil and Gas Co.'s Schallert No. 1 shows that the salt is still relatively high within 800 feet of the foot of the ring of hills. The symmetry of the surficial expression of the dome is assumed to express the symmetry of the underground structure and accordingly the salt core is assumed to be circular rather than elliptical in plan. The edge of the salt, therefore, is judged to lie median in position between the crest of the ring of hills and the locus of a point 800 feet in from the foot of the hills. Accordingly the position of the edge of the salt is placed low down on the inner slope of the ring of hills. The National Oil Co.'s Schallert No. 2, now drilling, is apparently located about on the edge of the salt. The chances would seem to be about even of its hitting the salt around 2,500 feet or of its missing the salt altogether.

If there is any considerable development of cap-rock at that point it should strike it.[4]

The cap-rock is poorly developed at Palangana. In the two Sinclair Oil and Gas Co.'s wells there was 30 feet of hard, white "lime" immediately overlying the salt. The cuttings, according to Kennedy,[5] looked as if this "lime" might be gypsum (anhydrite?). Three hundred feet above this bed, there is 17 feet of white "lime" overlain by 42 feet of "gypsum" and "mica" (probably selenite). In the National Oil Co.'s Schallert No. 1 there was 15 feet of "mica" (probably selenite) immediately above the salt. Above it 110 feet there was a 70 foot bed of "lime" overlain by 30 feet of "gypsum" and "mica." One hundred and sixty feet above the latter bed there was an 18 foot bed of "gypsum" and "mica" overlain by 22 feet of "lime rock." The correlation of these beds with those in the Sinclair wells is doubtful. The upper beds in each case seem to be correlative. The 15-foot "mica" bed of the National Oil Co.'s well may correspond to the 30 feet of "lime" in the Sinclair O. & G. Co.'s wells or it may be the 70-foot "lime" which corresponds to that latter bed. These upper beds may be genetically connected with the cap-rock in origin or they may be stray beds such as are sometimes found away from the immediate vicinity of a salt dome. It should be noted, however, that the Sinclair O. & G. Co.'s Gravis well had only two thin limestone beds. The Empire G. & F. Co.'s Palangana No. 1 encountered many thin beds of rock, some of them limestones, but the main cap rock was not encountered.

The detailed structure of the beds around the central core is

[4] The National Oil Co.'s Schallert No. 2 was recently announced, officially, to have encountered salt at 1019 feet (574 feet below sea level). The most recent report, apparently authentic, is that the well went through 101 feet of salt and into gumbo (drillers' term for clay) at 1120, into sand at 1136, and is now standing at 1138. The salt encountered in this well may be a lense above the main salt mass or a tongue projecting out from it as at Anse la Butte. The slope of the top of the salt on the east must be much less in any case than it is shown in Fig. 60, but until more information is available, the situation will remain in doubt.

[5] Kennedy, Wm., Report on Palangana to H. A. Speer, unpublished.

not known. Two wells have been drilled off the salt, the Empire Gas and Fuel Co.'s Palangana No. 1 on the edge of the dome, and the Sinclair Oil and Gas Co.'s Gravis No. 1 two miles to the northeast. Their logs, however, do not present any clues for correlation from the one well to the other.

A feature that is attracting much local curiosity at Palangana is a "breathing" well that was put down near the National Oil Co.'s Schallert No. 2 in an unsuccessful attempt to get water. The normal behavior of the well according to Mr. Lee, field superintendent of the National Oil Co. at Palangana, is as follows:

| | |
|---|---|
| Morning | Sucking in |
| Around 9 o'clock | Quiet |
| Forenoon and early afternoon | Blowing out |
| Around 4 o'clock | Quiet |
| Early evening | Sucking in |

Its behavior as seen by the writer was as follows:

| | |
|---|---|
| 9:00 A.M.—After a clear cool night | Sucking in |
| 2:30 P.M.—Clear warm day, almost hot | Blowing out |
| 4:15 P.M.—Clear warm day | Quiet |
| 3:15 P.M.—Cool cloudy day with spits of rain | Sucking in |

Mr. Harris a former driller on the National Oil Co.'s No. 2 adds that occasionally he has seen it sucking in at noon time and that twice at 7:30 P.M. he has seen it quiet and once sucking in.

The well blows out with a light cool breeze that is readily noticeable to the hand but that barely affects a rather stiff cotton handkerchief. The well is four inches in diameter, is 42 feet deep and is drilled in a rather porous tufaceous-looking siliceous limestone. On account of the incompleteness of the observations and the lack of the proper knowledge of the meteorological conditions, it is dangerous to draw conclusions in regard to the cause of the breathing. The control would seem possibly to be the local temperature affecting the local atmospheric pressure.[6]

[6] For notes on breathing wells see: J. D. Harris, Geol. Surv. of Louisiana, Report of 1905, Bull. No. 1, p. 60; and E. H. Barour, U. S. G. S. Water Supply, Paper 29, 1899, pp. 78–82.

OIL AND GAS.

There are three general types of occurrence of oil on a salt dome; in the relatively flat-lying shallow sand lenses above the cap; in the rock and cavities of the limestone or gypsum cap that covers the top of the salt core; and in the lateral, steep-dipping, often deeply buried sand lenses on the flanks of the dome. The presence of the oil is often indicated at the surface by gas seeps, oil seeps, oil and gas in shallow water wells, and paraffine dirt.

On Palangana there are none of these surface indications of the presence of oil and no important shows of oil or gas have been found in any of the wells drilled on the dome. The first Sinclair O. & F. Co.'s well had no show of oil or gas. The second had a small show of oil at 398 feet. There was no notable show of oil in either the first National Oil Co. well or in the Empire G. & F. Co.'s Singer well. The Sinclair O. & R. Co.'s Gravis well had a small show of gas at 959 feet, enough gas at 1,400 feet to cause a severe blowout, and a small show of oil at 2,060 feet. Four miles south of Palangana there is the old shallow field of the Piedras Pintas dome that is still producing a small amount of oil, from 250–350 feet.

The three wells that went into the salt, the Sinclair O. & R. Co.'s Nos. 1 and 2 and the National Oil Co.'s No. 1 are sufficient to condemn the top of the dome. There are sands present above the cap but they are apparently not oil bearing. These sands probably lense in and out and there is a possibility that away from the vicinity of these three wells a local lense might be found that would prove oil bearing but the probability is extremely small. There is slight possibility, also, of there being any oil found in the cap rock. These three wells show that it is only twenty feet thick and report no oil from it.

The lateral sands might be condemned by some on the strength of the dry hole of the Empire G. & F. Co.'s Palangana No. 1. The condemnation of more than the forty acres surrounding the well, however, is not justified. The productive area of many of the salt dome oil fields is extremely small. That of so productive a pool as West Columbia which up to April 1, 1920, has pro-

duced 10,084,000 barrels of oil, is only fifty acres.[7] Dry holes are in many cases only a stone's throw from big producers. This well furthermore was a rotary well drilled under contract. Unless extreme vigilance is used, oil may be sealed back by the pressure of the heavy column of mud and be missed. In a well drilled by contract, furthermore, there is often a tendency to drill for speed and depth and oil sands may thus be missed. The presence of oil in sufficient quantity to justify commercial extraction at Piedras Pintas shows that oil is present in the immediate vicinity of Palangana. It becomes a question of finding a sand that was favorably situated to catch and hold the oil. But as such a sand, if there is one, may have an area of the magnitude of only 50 acres, a long drilling campaign may be necessary to find it. But in this it will not differ from most of the salt-dome fields.

### AGE OF THE DOME.

In Texas there are two belts of salt domes, an inland belt comprising the Keechi, Palestine, Butler (West Point), Brenham groups of salt domes, and the coastal belt comprising those nearer the coast. Largely on the basis of the stratigraphic conditions prevailing, but partly on account of the recent doming of the present surface that is manifest in the surficial mounds of many of the coastal salt domes, there is a tendency to hold that the domes of the inner belt were formed in the late Cretaceous or early Tertiary, and the domes of the coastal belt in Miocene or post-Miocene time. The recent doming of the surface can, in part at least, be accounted for by the hydration of the anhydrate of the cap to gypsum, and may not indicate any primary movement connected with the formation of the salt dome proper. The inland domes are all well dissected and in that respect contrast strongly with the coastal domes, whose surficial mounds, even in the case of such a mound as Davis Hill, rising 200 feet above the general level of the surrounding country, show the effects of but slight erosion.

Physiographically Palangana resembles the inland belt of

[7] The field has been much extended by a well completed late in July, 1920.

domes much more than the coastal belt and may therefore be of that older age. The more considerable erosion that Palangana has undergone may, however, be due to the fact that it is more favorably situated for erosion than the domes of the coastal belt. It is apparently older than the plateau level of the top of the cuesta and the Reynosa does not seem to have been greatly affected by the doming. How much the Lagarto and Lapara Beds were affected is not known.

## ORIGIN OF THE DOME.

The origin of salt domes is still a much disputed question. There is a general tendency among geologists who have studied salt domes to recognize that the salt core is intrusive. The mechanism of the intrusion is a disputed question and no satisfactory explanation of it has as yet been formulated. With the little exploration that has been done to the present, Palangana offers no new evidence on the origin of salt domes and the various theories that have been advanced[8] will not be discussed here.

903 Rusk Ave.,
Houston, Texas.

[8] G. D. Harris, "Rock Salt in the State of Louisiana," Bull. No. 7, Geol. Surv. of La., 1907; E. T. Dumble, "Origin of the Texas Salt Domes," *Bull. A. I. M. E.*, No. 142, 1918; E. L. De Golyer, "The Theory of the Volcanic Origin of Salt Domes," *Bull. A. I. M. E.*, No. 19, 1918; G. S. Rogers, "Intrusive Origin of the Gulf-Coast Salt Domes," Ec. Geol., Vol. XIII., No. 6, 1918; F. F. Hahn, "The Form of Salt Deposits," Ec. Geol., Vol. VII., No. 2, 1912.

# TUNGSTEN DEPOSITS OF BURMA AND THEIR ORIGIN.

J. Morrow Campbell.

## INTRODUCTION.

Burma and the Malay Peninsula consist essentially of a series of parallel mountain ranges, the axes of which are slightly west of north and east of south. The valleys between them vary in type from deep rocky ravines to wide fertile plains, depending on local conditions.

These great ridges were produced by granite thrust upward in the molten condition which penetrated to only a limited extent the overlying sedimentary rocks. No evidence has yet been obtained by which we can fix definitely in what geological period these uplifts took place.

Denudation has removed much of the overlying sediments and exposed granite in many places. These exposures vary in area from a few acres to hundreds of square miles. They occur much more frequently in the narrower portions of the peninsula where rainfall is more abundant and where debris more readily reaches the sea than they do in the north. The average vertical amount of rock denuded in the south has been very great, the zones of low and intermediate temperature ores having been removed, copper, lead and zinc found in the north have disappeared and ores of high temperature type, tin and wolfram, are comparatively abundant.

We are concerned at present primarily with tungsten ores, their mode of occurrence and origin, but the latter part of the subject involves the consideration of accessory minerals, especially cassiterite.

## ORE DEPOSITS.

The Tavoy District has yielded much the greater part of Burmese tungsten ore; for this reason and also because the mode of

occurrence there is more interesting than elsewhere, most attention will be given to it.

*Rock Formations.*—The greater part of the surface in the Tavoy District is occupied by an apparently single series of argillites, phyllites, quartzite and schist to which the name Mergui schist is applied. They are non-fossiliferous and probably of Silurian age. What appears to be a continuation of this series to the north in the Moulmein District is overlain unconformably by the Plateau Limestone, known to be the homotaxial equivalent of our Devonian.

Granite is found at the base of the Mergui schist, wherever exposed. It is highly acidic and very uniform in composition. Its components are abundant quartz, less abundant feldspar (orthoclase and microcline) and a little mica (biotite). Sometimes mica is practically absent. Hornblende is unknown, tourmaline has never been observed and the minor accessory minerals usually found in granite are conspicuous by their scarcity. In some exceptional cases the granite near its periphery is markedly porphyritic.

Metamorphism of the sediments in the vicinity of their contact with the granite is not usually strongly marked but mica and andalusite schists have been observed in several places. It is notable that where intense contact metamorphism occurs neither the granite nor the schist at the contact contain ore minerals though they may be found some hundreds of feet above. In every case in which the granite or the schist contains ore at the contact the latter appears to have been only very slightly metamorphosed and resembles the same rock a thousand feet above the contact.

*Mode of Occurrence.*—Tungsten ores occur in veins in granite near its periphery or in the overlying sediments from the contact to over 600 ft. and probably 1000 ft. or more vertically above it, or partly in both.

In granite they have been proved to occur, (1) As primary minerals, (2) in greisen, (3) in veins of quartz, quartz with mica, and pegmatite. Greisen is the result of alteration of part of the

wall of a fissure and is not ore-bearing unless the contents of the fissure are also.

In the "schist" tungsten ores occur in aplite dikes and quartz veins.

Typical ore-bearing pegmatite has not been observed to occur in sedimentary rocks, but it seems impossible to draw a hard and fast line between pegmatite and quartz veins, for the latter always contain some mica. Many veins in granite are partly or wholly filled by material consisting of quartz, mica, ore minerals (sometimes in great variety) but absolutely without feldspar, and to which no other name than pegmatite seems to be applicable.

Ore-bearing veins, whether in granite or sedimentary rocks, are usually narrow, rarely exceeding 5 ft. in width and generally much less, but are frequently numerous, especially in the schist. Their strike usually approximates the direction of the axis of the batholiths but great variations occur, some veins striking East and West and in other cases two series of parallel veins within the same area, differently oriented cross one another. In such cases the series striking more nearly North and South is older than that with easterly and westerly strike. Aplite dikes, whether ore-bearing or not, when occurring in ore-bearing sedimentaries are invariably older than adjacent quartz veins. With the exception of a very few long single ones, tungsten-bearing veins occur in groups parallel to one another in strictly circumscribed areas outside which no ore is found and no evidence of fissuring.

The great majority of wolfram mines in the Tavoy District are small patches, the length of which along the strike of the veins may be exceeded by the width. It is exceptional to find either dimension over 2,000 feet. Kadwe Mine, which has yielded hundreds of tons of wolfram, and at the top of which veins were so numerous that thousands of cubic yards of rock weathered *in situ* were remuneratively worked by ground sluicing, is less than 800 feet across.

The dip of the veins may be in either direction, it is seldom less than 60 degrees and generally not far from vertical.

The great bulk of Tavoy wolfram is won either directly from

quartz veins or from detrital material on hillsides below vein outcrops: very few true alluvial deposits in Burma are tungsten-bearing. Both greisen and pegmatite are occasionally rich, but the total amount of ore they yield is small. Tungsten ores occurring as primary minerals in granite have so far proved of economic value in only a few cases. Tungsten-bearing aplite is of scientific interest only, for its tenor is low and the dikes usually narrow.

The existence of wolfram as a primary mineral in granite and aplite has been questioned but the opinion of the writer has been endorsed by that of Mr. J. Coggin Brown, of The Geological Survey of India, after microscopic examination of thin slices of the rocks. Such granites have been observed to contain not only wolfram and cassiterite but scheelite, molybdenite and bismuthinite.

A feature that strikes one forcibly in connection with the smaller wolfram occurrences is the extraordinary number of them that are to be found on hill-tops. In one case there are four on one side of a stream and three on the other quite unconnected with one another and though the hills are less than 300 feet in height, in no case does the ore, rich on top, persist to the level of the stream below.

That most of the Tavoy veins are worthless within 300 feet below their outcrop is established and, though there are notable exceptions, we have no proof that payable ore persists in any case for a continuous vertical depth approaching a thousand feet.

The Mergui District, south of Tavoy, has yielded some wolfram but most of its veins are stanniferous and do not need any comment.

The Moulmein District to the north of Tavoy shows several ridges of granite. Here the overlying sediments have undergone intense metamorphism, much gneiss having developed. Ore-bearing veins are common but they contain cassiterite almost exclusively, the gangue being usually tourmaline pegmatite. No ore is found in the granite itself.

Farther north, along the same strike, at a distance of about 200 miles up the Salween river, on its right bank, in the Karenni State

there is an important tin and wolfram deposit worked by The Mawchi Mines, Ltd. This has not been visited by the writer.

On the Ataran River, east of Moulmein wolframite is known to occur, but the deposit has not been opened and its value is unknown.

In the mountains along the eastern edge of the plain north of Rangoon, traversed by the railway to Mandalay, erosion has laid bare granite for about 200 miles. Cassiterite is known to occur at several points, and here, at Byingyi in the Yamethin District, wolframite along with molybdenite was found and worked to a limited extent but the results obtained do not indicate that either these or the tin deposits are likely to be of much commercial importance. Tourmaline occurs commonly along this line.

Doubtless there are many wolfram occurrences both in the Tavoy District and other parts of Burma that remain undiscovered, more especially such as are not stanniferous. Tin has been searched for and recovered since ancient times in Burma by the Chinese, but tungsten ores, having been of no value until recently, were not sought. The country generally is mountainous and prospecting difficult. Tungsten deposits are more difficult to find than cassiterite for the former ores do not exist in alluvials except in close proximity to the deposits yielding them.

*Tenor.*—The average wolfram percentage won from the whole of the quartz mined in Tavoy is low, probably not over 1 per cent. It varies greatly at different mines, but few can claim a recovery as high as 2 per cent.

The mining and recovery methods practised are usually crude, a natural result of the tribute system with Chinese semi-skilled or totally unskilled labor. Loss is therefore heavy both in mineral going to the waste-dump and in concentration.

Extremely rich patches yielding as much as a ton in a few cubic feet of ore are not uncommon; the material around the vein-stuff may be poor or even barren for some distance, then another rich bunch may appear.

The extreme variability in the ratio between tungstates and quartz in different parts of veins is characteristic everywhere.

The cause of this appears to be that tungsten ores, especially wolframite, find very few points on the vein walls suitable for the commencement of deposition and that when development has commenced it tends to continue at and around these points only.

### MINERALOGY OF DEPOSITS.

*Ore Minerals.*—The principal ore mineral is wolframite and, as far as is known to the writer (who has not studied the quantitative composition), neither ferberite nor hübnerite has been proved to exist in Burma. The only other primary ore mineral is scheelite. The latter, though widely disseminated, does not occur alone but always associated with wolframite. Much wolfram concentrate, as exported, contains a few per cent. of it.

In several mines where cassiterite is practically absent, wolframite and scheelite occur intimately intergrown and in such cases, if unaltered by acid, it is milk-white. When cassiterite exists in abundance in veins with wolframite, scheelite is usually either absent or present in only very small quantity.

It is a curious fact that wolframite on analysis invariably yields an appreciable quantity of tin even in cases in which no cassiterite is known to exist in the vicinity.

*Accessory Minerals.*—These are of great importance in relation to the origin of wolfram and cassiterite.

Mineralizers such as fluorine, chlorine and boron have been assumed in the past as being invariably present in tungsten and tin-bearing veins. If these metals were introduced pneumatolitically the existence of these elements in adequate quantity would seem to be imperative.

The Tavoy veins contain very little fluorite or topaz, though both are widely disseminated in small quantities not only in ore-bearing but in barren veins. Minerals containing chlorine, such as apatite, are rare. Not a single crystal of tourmaline has been found in spite of the most assiduous search. Columbite is unknown and it is unfortunate that its existence along with tourmaline, reported in error, is quoted on practically every occasion on which Tavoy deposits are referred to abroad.

Lately the writer received a sample of a mineral, probably samarskite, consisting of the niobates and tantalates of rare earths and containing both tungsten and tin, from some distance east of the Salween River in the lower part of its course. This is hundreds of miles from Tavoy however and, though said to occur in large quantity, the pegmatite carrying it does not yield ore of either tungsten or tin in other form.

Pyrite is invariably present with wolfram, and cassiterite occurs in the majority of veins. Molybdenite is widely diffused and occurs most commonly at and below the bottom of the wolfram zone. The total quantity existing is so small as not to warrant the adoption of the special methods necessary for saving it.

Native bismuth is found in a few mines. Only at Kanbauk has it been recovered and less than a ton has been exported so far. Bismuthinite occurs in a considerable number of mines but usually in very small quantity. It is not recovered. When weathered it yields the basic carbonate, bismutite, which is largely included in the concentrate from sluicing and is usually exported without separation.

Arsenopyrite, chalcopyrite, magnetite, hematite (specular), ilmenite, stibnite, pyrrhotite, sphalerite, galena and siderite also occur but not commonly. The sulphides enumerated above are invariably introduced into the veins by reopening at a period long subsequent to that when tungsten ores developed. Pyrrhotite occurs in only a few veins and is invariably accompanied by sphalerite and galena. Siderite occurs in Kanbauk Mine in association with wolframite and molybdenite.

Garnets are found here and there but are much rarer than is usual in most tin-bearing areas. The same applies even more strongly to beryl, zircon and rutile. Tourmaline occurs in abundance in the coast range as well as in the mountains on the Siam frontier northeast of Tavoy but never in the same veins as tin or tungsten ores.

*Mineral Relations.*—Molybdenite, when present, is invariably the first ore to develop. It is often closely associated with mica, evidently paragenetic. Wolframite follows, often enclosing both

molybdenite and mica. It develops in different ways, a common form being in groups of divergent crystals. These may form on one or both walls and may or may not meet, but, even if they do, it is very exceptionally that they fill the whole available space making a solid mass from wall to wall. Interspaces of the crystals are filled with pyrite, cassiterite, scheelite, and quartz, none of which has been observed in any case to precede wolframite. Pyrite certainly, and cassiterite probably, sometimes develop simultaneously with wolframite. Cassiterite and scheelite rarely, if ever, exist in the same interspace but any other pair of the above four minerals is of common occurrence.

The vein space between wolfram crystal groups is usually filled with quartz but cavities are not uncommon into which wolframite crystals, either free or partly enclosed by quartz, project. It is from such cavities that the best specimens of wolframite crystals are obtained. Cassiterite sometimes develops on the faces of wolframite in such positions. Cavities in veins are comparatively common and they are usually lined with quartz crystals. In Zinba Mine there were several cavities in which the quartz crystals were unusually large and well developed, some with terminals at each end, many were over an inch in diameter, transparent and contained enclosed within them numbers of crystals of bismuthinite as well as mica.

Crops of well-formed quartz crystals developed on wolframite occur at Yamazu Mine with the former enclosed in scheelite. More rarely cavities are found lined with scheelite crystals.

In some cases wolframite and scheelite are found intimately intergrown, having obviously developed simultaneously.

A peculiarity of tungstates is that they develop in comparatively large, never minute crystals. Molybdenite similarly forms comparatively large crystals, whereas bismuthinite is very commonly found in microscopic crystals scattered throughout quartz and giving it a characteristic smoky appearance.

There is one very interesting mode of development of wolframite. Crystals grow from a few points on the walls in bladed form usually about one eighth inch thick, an inch wide and as

much as a foot long; from these other similar ones develop and so on until perhaps 10 per cent. of the total vein space for many feet of its length and depth is occupied by these ramifying crystals. The space is then filled with quartz. This is unquestionably the result of crystallization from a solution.

The smallest wolframite crystals observed occur in acicular form scattered through quartz and quite unconnected with one another. This, at first, suggests paragenesis of wolframite and quartz but such is unlikely as it has never been observed elsewhere. The true explanation probably is that the crystals were formed within a silica gel which subsequently crystallized.

The simultaneous occurrence in vein pegmatite of such a variety of minerals as quartz, mica, wolframite, scheelite, pyrite, chalcopyrite, molybdenite and bismuthinite appears to be incapable of an explanation consistent with the phenomena of the occurrence of the same minerals in veins, except on the assumption of their crystallization within a gel.

The amount of wolframite deposited in a vein must be proportional to the amount of heat absorbed from the ore-bearing fluid by the vein walls and the rate of loss of heat must determine the rapidity of deposition and largely also physical variations in the mineral.

The laboratory examination of the contents of veins reveals many interesting facts, for example, solid masses of wolframite and cassiterite are found with mica crystals completely enclosed within them. Bismuthinite is also found similarly enclosed, not only in wolframite but in fluorite, quartz and molybdenite. When thus enclosed its surface is not a series of crystal faces but is rounded and in cross section circular.

Lack of space forbids further enumeration, but this work produces the strongest conviction that the above facts can be explained only on the assumption of deposition from solution.

Some tungsten-bearing veins contain much fluorite, others, none. The common association of fluorite with cassiterite was largely responsible for the theory of the pneumatolytic origin of the latter, yet the well-known association of the same mineral with

galena had no such result. At the same time the function of silica, which always accompanies tin and tungsten as well as many other ores appears to have been almost entirely neglected.

The occurrence of tourmaline in wolfram and tin veins in Burma is curious. None whatever occurs in Tavoy, yet it is common in the Mergui District to the south and also to the north at Amherst, Moulmein and in Upper Burma. In the Amherst tin veins, tourmaline is almost invariably present, and, as it is quite commonly enclosed by cassiterite, it developed first.

The evidence of high temperature ore veins in Burma proves that tourmaline and fluorite have no genetic connection with tin and tungsten ores and that their occurrence together is entirely fortuitous.

### DECOMPOSITION OF WOLFRAMITE AND SCHEELITE IN NATURE.

It has been said that Tavoy wolfram is largely won from alluvials: this is untrue.

Very few true alluvials in Burma are tungsten-bearing. The debris from strata carrying even very numerous rich wolfram veins contains no tungsten after having been transported even a few miles in nature. A good example of this is the Hermyingyi Mine, one which has frequently yielded over 100 tons in a month of mixed concentrate, mostly wolfram. The richest portion of the mine is in high hills around a hollow opening out into the Maungmeshaung Stream. Within the hollow, water-worn fragmental material with a high proportion of large boulders has collected over an area of several acres and to a depth of over 10 feet in places. This has been transported only a short distance by water, but it must be regarded as an alluvial in the strictest sense of the word. It is rich in both wolfram and cassiterite. On going down the Maungmeshaung Stream the amount of wolfram in the gravel of its bed diminishes so rapidly that less than seven miles from the mine there is none. There is a similar wolfram bearing alluvial at Kanbauk Mine but parts of it have undergone laterization and these are not wolfram bearing though they are still stanniferous.

Wolfram may be removed from an alluvial by comminution or by solution or by both combined. In every case comminution must have accelerated the process of solution, but alone it cannot account for the entire removal of tungsten. In the case of the laterized portions of an otherwise wolfram-bearing alluvial being barren, the comminution theory fails entirely and we are compelled to regard the removal as having been effected by the solutions that caused laterization. We know the nature of these and it seems probable that the active agents are alkaline carbonates in solution in unoxygenated, carbonated water. Though the work of Mr. R. W. Gannett[1] in the laboratory seems to indicate that such solutions have no solvent action on wolfram (which was probably due to the time allowed being very short compared with the periods during which natural solutions act) the fact remains that ordinary alluvial in Burma contain no trace of tungsten (except in mineral completely encased in quartz) nor does a ferruginous residue remain.

Fragments of wolfram from old eluvial often display well-etched surface markings—a well-known result of the action of solvents on crystalline substances. Phenomena in Burma indicate that wolfram is slowly and completely dissolved by ordinary ground water.

When wolfram is exposed to the action of oxygenated water, for example in vein outcrops, we frequently find the acid radicle leached, and a residue of ferric and manganese hydrates left. The writer has samples in which the process was incomplete and in which corroded wolfram is to be seen after removal of the hydroxides by HCl. Pyrite usually occurs in the same veins with wolfram and scheelite, oxygenated water acting on this produces sulphuric acid. This slowly attacks tungstates; but scheelite before wolfram; calcium sulphate in the former case or ferrous and manganous sulphates in the latter, all soluble in water, result, the two latter being oxidized with precipitation of the hydrates on adjacent solids, often as a glossy black coating.

The microscope frequently reveals cracks in oxidized wolf-

[1] Econ. Geol., Vol. XIV., pp. 68–78, 1919.

ramite to be filled with a hydrate of ferric oxide, probably xanthosiderite, in transparent crystals, bright red by transmitted light.

Anhydrous tungstic oxide has not been observed, it appears always to take up water. When derived from wolframite it remains behind as a yellow powder. Decomposition in the case of scheelite takes place with comparative rapidity along cleavage planes and cracks in which tungstic hydrate in two apparently different forms is to be observed under the microscope. These occupy the whole space of the original scheelite and the action proceeds until a solid mass of hydrate, practically without calcium, remains. Such specimens are uncommon, for tungstic hydrate is readily dissolved by alkaline carbonates in ground water. Tungstic acid resulting from the removal of the basic radicles from wolframite has never been observed to occupy the whole space of the original mineral.

Alkaline tungstate solutions are sometimes decomposed by acid with deposition of tungstic hydrate in which case tufts of radial yellow crystals are formed, commonly in crevices.

Most of the tungstic acid seen in Burma is the result of decomposition of scheelite. This mineral when partly decomposed assumes a yellow color and is usually mistaken for tungstite, hence the popular error prevalent here that scheelite very seldom occurs.

Tungstic acid from wolframite is often masked by inclusion in ferric hydrate yielded by the oxidation of ferrous sulphate.

Secondary scheelite, usually honey-yellow in color, is not uncommon in crevices as well-formed crystals. The largest yet seen was less than 1 mm. in length, most are much smaller and therefore are ordinarily not observed. This probably results from the action of calcium sulphate solution on alkaline tungstate in an excess of alkaline carbonate solution. Hydrated calcium sulphate in brilliant white scales has been observed crystallized with tungstic acid, no scheelite being present.

ORIGIN OF DEPOSITS.

*Vein Fissuring.*—Since the fissures now occupied by ores in Tavoy are of an unusual type it is fortunate that the conditions there offer exceptional opportunities for studying the problem of their origin. A concrete case affords the best illustration.

In the Kadwe Mine there are many wolfram-bearing veins, the outcrop of which lie within a circle less than 800 feet in diameter, entirely in sedimentary rocks. At a depth of 600 feet below the highest outcrop a cross-cut, also entirely in altered sedimentaries, indicates that only three veins persist to that depth and the only ore mineral present (and that in mere traces) was molybdenite. Another cross-cut 200 feet higher up revealed the existence of more and wider quartz veins but, while carrying wolfram, they were of no economic value. At the outcrops the veins were most numerous and richest, their number and tungsten content gradually fell until at 400 feet down they were worthless. This mine is typical of quite a number in the "schist."

The exact vertical distance from the outcrops to the granite periphery is not known, but there is reason to believe it is under 1,000 feet.

The matter filling the veins had its source in the batholith and there also was situated the force which caused the fissuring. Cracking due to cooling could not have been the cause, for the veins increase in both width and number the farther they are away from the granite, and the reverse would be the case with shrinkage cracks.

The force that produced these fissures in an area less than 800 feet in diameter at a horizon more than 600 feet above the granite periphery could not possibly have been deep-seated within the batholith nor could it have operated from anything but a very small area. It was one of almost explosive violence acting within a small area around a point practically at the surface of the batholith. These series of veins within circumscribed areas are invariably mineralized and moreover very little wolfram is found outside such areas. The connection between mineralization and this type of fissuring is so constant that it cannot be regarded as

accidental. We are practically forced to seek a common cause for both.

*Deposition of the Ores.*—The vertical position of the ore-bearing portions of veins with reference to the periphery of the granite varies greatly. It is generally admitted that tungsten and tin are carried upward from the granite magma in a fluid state and their deposition in veins was determined usually, if not invariably, by cooling. As the upward movement of fluids in veins was probably not rapid it follows that the temperature of such fluids at any point was very little above that of the vein walls. Abstraction of heat from the ore-bearing fluid must raise the temperature of rocks traversed by veins but, considering the enormous volume of rock and the slow rate of movement of the fluid no very great rise could result. We may assume therefore that the temperature of the rocks at the time of fissuring is the main factor in determining both where ore deposition will commence above and also cease in depth. If the temperature gradient in the rocks is steep, the vertical range of any particular mineral deposited in a vein will be small; but if the gradient is gentle, ore will develop through a much greater vertical depth. The temperature gradient in rocks should therefore be used as a guide to persistence in depth of ore deposits. The Morro Velho Mine in Brazil affords a good example of the application of this principle. In that mine, ore persists to over 6,400 feet vertically—a very unusual depth, while the temperature of the rocks in the mine rises only 1 degree C. per 140 feet of depth—an unusually gentle gradient.

Unfortunately we do not know at what temperature either tungsten or tin passes from the fluid to the solid condition. It is not even agreed whether the fluid referred to is liquid or gaseous. If we knew the former there would be little doubt about the latter. The only evidence available is indirect.

Pneumatolysis demands that the temperature be one at which, under the local pressure, water is in the gaseous state. Even if the pressure at depth is not greater than the hydrostatic head, water cannot exist in the gaseous condition above 33,000 feet

near which the normal temperature increase, putting it as low as 1 degree C. per 100 feet, would give us 365 degrees C.—the critical temperature of water. It is unlikely that water is capable of existing as a gas in the normal crust below its critical temperature. This may not apply in the vicinity of batholiths within, say 20,000 feet of the surface; there the vapor pressure of water may overcome the static rock pressure below that temperature. The great depth at which it is known that tungsten and tin ores formed would probably involve such high static rock pressures that a temperature of 350 degrees C. may be regarded as the minimum at which pneumatolysis would be possible. We know that wolfram and cassiterite have developed in veins in sedimentary rocks 700 to 1,000 feet above the granite. If tin and tungsten were carried upward as gases it follows that all the rock in the vicinity of the veins must have been heated to at least 350 degrees C. and the lower portions to a considerably higher temperature. The effect of the prolonged action of aqueous vapor at such a temperature is well-enough known to justify the opinion that the walls of the Tavoy veins in the sedimentaries have not been subjected to such an influence. The rock in the midst of a series of wolfram veins is not different in any way from that far distant.

In reference to the magmas yielding them, there are two distinct types of tungsten deposits—high and low temperature. In the former the magma and the sedimentary rocks overlying it were so hot that the ore-bearing fluid passed up fissures for hundreds of feet above the contact before reaching strata low enough in temperature to permit the ore minerals to be deposited. In the low temperature type, which is most common, the magma at its periphery and the sedimentary rocks above were so cool that the ore-bearing fluids deposited all their metallic contents below the contact sometimes as components of the granite at its periphery but usually in fissures. A few deposits, of which Hermyingyi Mine (the largest wolfram producer in the world) is an example, belong to an intermediate type in which the ore-bearing portions of the veins lie partly in the schist above and partly in the granite.

Vein fissures appear to have formed rapidly and remained open till filled with solids. Simultaneously with their formation they were occupied by liquid from the magma which, being practically incompressible, would serve almost as well as solid matter to resist the forces tending to close them. It is hardly credible that a number of narrow-branched fissures extending for hundreds of feet vertically could have remained open if occupied only by gases, which pneumatolysis demands.

The magma yielding Tavoy granite, with its tungsten and tin ores, undoubtedly contained and gave off copper, zinc, and lead sulphides. The solutions carrying them probably passed upward through the same fissures that are now the ore-bearing veins, and deposited their metallic contents far above the tungsten and tin in a zone since removed by denudation.

In Cornwall it is well known that the ore content of some veins changes from copper above to tin below. It is probable that the two metals were deposited almost simultaneously. This is obviously impossible if tin is of pneumatolytic origin. The two metals appear to have been borne upward through the fissures in solution in the same medium and each ore deposited where the temperature was suitable.

When copper, zinc, and lead sulphides occur in the veins of Tavoy they are very small in amount and occupy fissures formed later than those carrying tungsten and tin, and usually the second fissuring appears as a reopening of the first, in which case we find wolfram cracked and filled with, say, chalcopyrite or even several feet in thickness of chalcopyrite and pyrrhotite with blende, galena, and quartz parallel with or traversing wolfram veins. These successive re-openings provide perfect evidence as to the order of deposition: wolframite came first followed by cassiterite then in succession chalcopyrite, pyrrhotite, blende, and galena.

*Segregation of Ores in the Magma. Pneumatolysis.*—In the differentiation of primary rock magma into basic and acid fractions the ore minerals under consideration always accompany the most highly acid differentiate. This portion of the magma, which on cooling under pressure yields granite, must be admitted to

have been liquid for a period sufficiently prolonged to be regarded as a solution in which the components were evenly distributed through large volumes of it. It undoubtedly carried the metals in solution.

We must endeavor to ascertain how tungsten was dissolved and to trace the changes whereby tungsten in a very dilute solution of a specific gravity below 2.6 is segregated so as to occur in the rock near its periphery in the form of solid minerals of density about 7. Obviously the segregation could take place only by the metals being carried upward either as gases or liquids.

In the past most geologists have apparently accepted the gaseous condition as that in which tin has segregated from the magma. The origin of tungsten minerals does not appear to have been closely studied. Tin and tungsten are often closely associated in nature and we have proof that they are homogenetic.[2] In many mines in Tavoy District cassiterite and wolframite have developed in actual contact within veins. Ores from most of these mines have been carefully examined by the writer and hundreds of examples prove that wolframite developed before cassiterite. The evidence is absolutely incontrovertible. So far not one unequivocal specimen has been found in which cassiterite formed first. Some examples suggest simultaneous development but they are rare. Wolframite is thus proved to have developed at a temperature probably higher than cassiterite and certainly not lower. They must therefore be either both of pneumatolytic origin or both of aqueous origin.

The phenomena of the occurrence of tungsten and tin ores here can not be reconciled with their expulsion in the gaseous condition from the magma.

Gas in solution may be liberated by one of two causes: either the solvent must cool and partly solidify or the pressure sustained by the solution must be diminished.

Solidification of the magma takes place slowly from the periphery downward and dissolved gases, if liberated on cooling, should

[2] See also Ferguson, H. G., and Bateman, A. M., ECON. GEOL., vol. 7, p. 257, 1912.

be found in condensed condition at varying depths within the granite since it is probable that liberation would take place only in the zone of partial solidification as it extended downward. These ares, however, are found exclusively near the periphery; thus it is improbable that cooling of the magma was the cause of their evolution as gases.

Evidence indicates that the segregation of metals, with attendant silica and water, took place within the magma during a period not of diminishing but of increasing pressure which culminated in fracture of the overlying rocks, that the magma was liquid during the whole time and that it contained much more than the normal amount of water, silica and metals in the immediate vicinity of the point of fracture previous to the time when fracturing caused release of pressure.

Suppose, however, for the moment, that there is some fallacy involved in the above reasoning and that metal bearing gases were given off. They would pass upward and collect at the highest points on the periphery just as oil does in the crests of anticlines and domes. Not only metal-bearing gases, however, but water and silica, also as gases, would have to collect simultaneously. Three difficulties now arise: 1. Tungsten and tin ores, while found sometimes at the highest point, do not usually occur there but at or above any part of the periphery. 2. There is no trace of evidence that water is ever given off in the gaseous conditon from a granite magma in course of consolidation. 3. We know of no means by which silica could be given off in the gaseous state except as fluoride and in this specific case fluorine does not exist in quantity adequate to act as a carrier of metals much less of silica. In the case of wolframite the pneumatolytic theory would demand the presence of both manganous and ferrous compounds in the gaseous state and, with scheelite, calcium also in gaseous form. It may be argued that the presence of silica as a gas is not essential—this is not the case. In Tavoy we have quartz crystals in which cassiterite is imbedded in such a way as to prove conclusively that the two oxides developed simultaneously—either both are pneumatolytic or neither is.

Tungsten-bearing veins were not formed at one period only. In the same area we find as many as three series of them and, as they intersect one another, there is no doubt of the order in which they were formed. There are, therefore, in some cases three successive periods in which the pressure at the surface of the magma at points where ore minerals segregated, increased to such an extent as to fracture the overlying rocks. This seems to indicate that the segregation of the ores was a progressive process over a considerable length of time and that pressure increased during that period until fissuring on one or more occasions took place.

Tungsten ores are invariably accompanied by large quantities of silica which was not introduced in a state of fusion. It certainly came from the magma mixed or combined with water. This silica-water was probably variable in composition and we do not know the minimum ratio of water to silica that could maintain the liquid condition at any particular temperature and pressure. It is probably safe to assume that water was generally in excess. The writer has already put forward the theory that this silica-water from the granite magma carried tungsten, tin and other metals in solution and it was from this medium that they were deposited in veins.

Tin has been reported so often as present in various natural waters and in the solids deposited from them that little doubt can remain as to the existence in nature of aqueous solutions of tin oxide.

We know that silico-tungstic acid and its alkaline salts are soluble in water and stable even above 350 degrees C. Surely it is more credible that these exist in nature than tin fluoride and hydrofluoric acid.

As the evidence is strongly in favor of tungstates having been deposited from liquid and not gas, we assume as a working hypothesis that they along with tin and other associated minerals existed in the magma and were transported thence to veins in silico-aqueous solution.

We must next consider in what condition water exists in rock magmas, with special reference to the acid differentiate, in order

to understand the mode in which the metals existed in solution there.

Few geologists can be entirely satisfied with the theory of magmatic differentiation as at present expounded. The writer believes that the essential principle explaining the liquefaction of magmas and the development of minerals therefrom is not understood. Magmas are said to contain water though the lowest temperature during solidification of even the granitic portion must be far above the critical point of water. No hydrated mineral is of magmatic origin: some contain hydroxyl, none water: the difference is fundamental. If present in magmas as such, water can exist only as a gas in solution in liquid. The presence of water in this supposed form is credited with lowering the melting point and increasing the liquidity of rock melts, though its mode of action does not appear to have been rationally explained. A rock magma is a very complex liquid and therefore it is difficult to reason directly as to the function water as a gas dissolved in it would perform. Fortunately this is not necessary for we have the last magmatic fraction, the acid mother-liquor; it is more simple in composition, frequently consisting of silica and water almost entirely. Here, there is evidence of water in the liquid form along with no other substance that could materially affect it but silica, and the temperature is certainly above the critical point of water. To suppose a gas, say, 150 degrees C. above its point of liquefaction and a solid over 1,000 C. below its melting point to so affect one another, without chemical combination, as to produce a liquid apparently stable through a wide range of temperature and pressure seems absurd. Because a magma gives off water on the solidification of the greater part of its components is no proof that it contained water qua water while liquid. Its acid fraction exudes a liquid which, at reduced temperature and pressure, yields principally quartz and water. Certain minerals resulting from magmatic differentiation, such as biotite are said to contain water, when heated at atmospheric pressure they give off water: it was not present as such in the mineral, however, but as hydroxyl. The so-called water of the mother-liquor

must be present in combination, and with silica since no other substance is present in adequate quantity with which to combine. The only form in which it could combine with silica is as hydroxyl, a form in which we know it exists in some magmatic minerals. We have good reason to believe that so-called water in the main magma is also present as hydroxyl in combination with silica.

In regard to the composition, we have reasoned back from the mother-liquor to the magma. Let us now follow back the same liquor, regarding it as the magmatic solvent. The last essential mineral to develop in granite was quartz. No one will argue that it developed by crystallization from molten silica: it must have been in solution.

On the present hypothesis the granite magma was a solution in a large excess of silicic acid mainly of the various metallic radicles remaining after the formation of the minerals of the basic differentiate and from which it separated, not on the crystallization of the latter but gravitatively, owing to immiscibility. From the granite magma biotite develops first, in solid form, followed by potash feldspar. These two form a sponge-like mass the interspaces of which are filled with a highly siliceous solution which deposits quartz from solution in it, consolidating the whole and the solvent retreats upward and is ultimately expelled as mother-liquor.

The amount of basic radicles, other than those of tungsten, tin, etc., contained in solution in the liquor when expelled appears to depend on pressure more than on temperature.

It has been asserted that at high temperatures water acts as an acid even so far as to displace silica from silicates. The writer's experience points to the opposite conclusion, viz, that the function of hydroxyl in magmas is basic since it takes the place of basic radicles in magmatic minerals combining with, not replacing, silica. The chemical constitution of silicates is comparatively simple since silicon atoms in the molecule do not unite directly to one another but are linked by an oxygen atom. This is fortunate for mineralogists who otherwise might be faced by compounds of silicon comparable in number with those of carbon.

In tracing tungsten in solution from the magma to the mother-liquor in combination with silicic acid we have sought to demonstrate the solvent power of silicic acid in general.

The following summary of suggestions regarding silica and water under magmatic conditions are put forward in the hope that they may be discussed and the truth arrived at:

1. That silicon in combination with oxygen and hydroxyl (or perhaps even with hydroxyl alone—$Si(OH)_4$ ortho-silicic acid) exists in magmas during the liquid and solidifying periods.

2. That silicic acid is a powerful solvent combining with metallic oxides, sulphides to a limited extent and even certain metals.

3. That from this medium magmatic minerals develop.

4. That silicic acid is capable of dissolving silica freely and, on cooling, deposits it as quartz, and at moderate temperatures is miscible with a large excess of water.

In general the solution and transport of metallic oxides, and to a lesser extent sulphides and metals, in silicic acid at elevated temperature and pressure and the liberation of ore minerals at lower temperatures and pressures seems to offer a solution of problems unexplained by our presently accepted theories. Many phenomena in auriferous quartz veins are readily explained on the assumption of the existence of soluble auro-silicates.

It is illogical to regard as fortuitous the invariable occurrence of tin and tungsten ores and the very frequent association of the great majority of other ores with quartz.

The next question is as to the origin of the water known to be given off by magmas. Believing it to be improbable that the crust of the earth at any depth could have contained water on its original consolidation, the writer, though fully appreciating the weight of evidence to the contrary, argues that it was all primarily of meteoric origin.

We have no means of arriving at even the roughest approximation to the amount of water given off by magmas on cooling. It is always accompanied by silica, so the amount of quartz and pegmatite found above a batholith seems to be the only criterion whereby we can judge as to the relative amount given off at different points.

Quartz at Tavoy is found in scattered veins, usually barren, and in groups of parallel veins invariably mineralized.

The ordinary theory of magmatic differentiation does not explain how water can collect at a number of points on the periphery in volume enormously greater than elsewhere and why our ore minerals collect there also. It does not seem credible that a highly aqueous solution of silica could collect in a number of very small patches on the periphery by *segregation from a still liquid magma.* If, however, this water came from the surface through fissures we have a simple explanation of its presence in large quantity at certain points, this also explains how metals are leached upward in the magma while still molten; why they are found at the periphery and in any position, not necessarily at the crest; why the violent localized force causing fissuring is invariably at the periphery, not deep down in the magma; why we have not one only but two and even three successive periods of ore segregation and fissuring always at the same point; and finally why the earliest-formed fissures are sometimes filled with mineralized aplite.

The writer had some hesitation in adopting this theory but did so solely because it is the only one that appears competent to explain all the phenomena recounted above.

## CONCLUSION.

As to whether magmatic minerals develop from silicic acid solution or not might be tested in the laboratory by attempts to synthesize the alkali feldspars in this way. Success in this direction would give very valuable information regarding magmatic temperatures and pressures.

It is probable that in the past we have erred in ascribing to substances the existence of which in magmas and magmatic liquids is unessential too much importance in ore solution and transportation.

Whatever may be the origin of water in magmas it seems to exist there as a liquid above its critical temperature in combination, as hydroxyl, with silica. This compound appears to be the

great magmatic solvent, and there is much evidence that silicic acid in aqueous solution performs a rôle in ore solution and transportation in nature of much greater importance than has been realized in the past.

RANGOON, INDIA.

# EDITORIAL

## *REGARDING MAGMATIC NICKEL DEPOSITS.*

The nickel deposits at Sudbury have often been described and from various viewpoints. There has always been a scarcity, however, of exact sections from this locality, those available being too diagrammatic; some open to doubt, because too suspiciously regular, others exhibiting the opposite direction. We therefore welcome a recent publication by the staff of the Creighton mine, presented by Mr. J. C. Nicholls at the Toronto meeting of the Canadian Institute of Mining and Metallurgy in March, 1920, and very recently published in the Bulletin. It deals mainly with the mining and smelting operations of the International Nickel Company but contains also a few illuminating notes on the geology of the mine and best of all an exact cross section. The Creighton deposit lies between granite and norite extending below the twentieth level, 1,400 feet below the surface, into granite; it is from 100 to 250 feet thick and looks very much like an intruded dike. A zone of mineralized norite up to 200 feet thick lies some distance in the hanging.

Other investigators have been busy with this same general problem from quite another aspect. We find that Professor J. H. L. Vogt, from whom little has been heard for some time, has been industriously investigating the solubility of sulphides in silicate magmas and vice versa. A volume of 132 pages embodies his results and presents the matter in conformity with his former publications on the silicate magmas.

Professor Vogt has also published a less technical paper better adapted to the understanding of the average geologist under the title "Die Sulfid-Silicat Schmelzlösungen" and this appeared in the *Norwegian Journal of Geology*. We summarize the following data from his interesting discussion.

Silicates are practically insoluble in sulfide melt, while the sulphides of iron and zinc are soluble to some degree (maximum 5 per cent. FeS) in a silicate melt. On the other hand Professor Vogt states that $Cu_2S$ is practically insoluble in basic silicate melts and declines to accept Wanjukoffs' results which seemed to indicate a somewhat notable solubility. Insoluble are also PbS and $Ag_2S$, while nickel sulphide may be very slightly soluble, though this solubility must be greatly decreased if FeS is also present in the melt, sulphur being a common ion.

Pyrrhotite is regarded as a solid solution of $FeS_2$ (not S) in FeS. Sulphide melts composed of FeS with a few percent. $FeS_2$ yield pyrrhotite; those with more $FeS_2$ crystallize into earlier pyrite and later pyrrhotite.

The nickel ores contain as a rule 70–80 per cent. pyrrhotite, 2–6 per cent. pyrite, 7–18 per cent. pentlandite and 4–9 per cent. chalcopyrite; the order of crystallization is (1) pyrite, (2) pyrrhotite, (3) chalcopyrite with a little pyrrhotite. The residual magma therefore becomes richer in chalcopyrite and this mineral thus often occurs around the periphery of the ore bodies or in veinlets.

Small crystals of ilmenite are common in these ores and evidently separated out at an early stage, in part contemporaneous with the pyrite; therefore $FeTiO_3$ is soluble in the sulphide melt. Magnetite is rare and the solubility of $Fe_3O_4$ in the sulphide melt it thus considered very small. Most of these deposits are found in norites. Rocks consisting of olivine, of bronzite or of hypersthene often carry much pyrrhotite with a little copper and nickel. In such rocks the silicate minerals are always idiomorphic against the pyrrhotite indicating that they crystalized in the presence of still fluid sulphide melt, though some corrosion is often observed. From the pyrrhotite veinlets of the same mineral frequently extend into the silicate. At atmospheric pressure the crystallization of the silicates would take place from 1200 degrees C. to 1300 degrees C., whereas the pyrrhotite melt congealed at a little lower temperature, probably at 1183 degrees which is the melting point of this mineral. Pressure would have little effect in changing

the temperature of consolidation. The influence of possible water and other mineralizers is not discussed.

In ordinary norites and gabbros the percentages of sulphides in solution may be a maximum of 1 per cent. just above the point when silicates begin to separate out. The sulphide separates out on the consolidation of the rock and remain fluid until the silicates are congealed. Therefore, the sulphides appear as the very latest minerals pressed in between the others.

It will be observed that this view exactly coincides with the results of Mr. E. Howe in his examination of the rocks of the Cortlandt series.[1] On the other hand, in the pyrrhotite-silicate rocks containing 10 to 50 per cent. sulphide, the explanation presented does not suffice, for only a small quantity of sulphides can have been in solution. The magma of these rocks must have contained two fluid phases, a silicate melt and sulphide melt.

We may then summarize Professor Vogt's ideas in stating that the original norite magma contained dissolved sulphides at temperatures high above that of consolidation, possibly more than one per cent. With lowered temperature the fluid, extremely mobile sulphide melt began to separate, making two fluid phases in the magma. The gradually separated sulphide melt sank towards the lower boundary of the laccoliths and gradually coalesced to greater, still fluid, sulphide masses. Pyrrhotite-silicate rocks represent solidified masses of two phase magmas enriched by the sinking sulphide. Finally the pure sulphide melt was pressed up along the margins and in brecciated zones of the congealed silicate rock.

The conclusion can of course not be avoided that the copper and nickel sulphides *are* soluble to some extent in the magma. The differentiation leading to the formation of sulphide deposits therefore begins with a separation into two fluid phases, while the development of the norite rock proceeds in the system fluid: solid *i.e.* by fractional and gravitative crystallization.

The differentiation of the sulphides in the pyritic ores is also to be regarded in the same light, *i.e.*, as a differentiation by crystallization.

[1] Econ. Geol., Vol. 10, 1915.

Professor Vogt discusses the influence of temperature and pressure but it is to be observed that he does not go into the question of magmatic water except to say that it has probably little effect on the order of crystallization. And yet, the consideration of the "offset" deposits formed in adjacent rock masses necessarily brings up this matter as well as that of other mineralizers, for instance arsenic, known to be present in these deposits. They universally also contain a very small amount of zinc blende, a mineral much more soluble in dry magmas than is the copper sulphide. The indications are that the sulphide melts of the magma are passed over into aqueous solutions, which were active in the formation of "offset" deposits as shown by the abundant development of chlorite. The question is: Did the sulphide melt contain water? If not, where did the water come from?

On the whole, the interpretation of the Sudbury ores as injected magmatic sulphides seems to be gaining ground.

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# DISCUSSION.

**This department has been established by the editors in order to afford to those interested in questions relating to economic geology an opportunity for informal discussion. Contributions are cordially invited either in the form of discussion of more formal papers appearing in earlier numbers or bearing upon matters not previously treated. Letters should be directed to the Editor, Sheffield Scientific School of Yale University, New Haven, Conn. The full name of the author should be attached to all communications.**

*Sir:* In the March number there are two very interesting papers on the origin of the Cobalt silver ores, showing that the source of the silver and the manner in which it reached its present position in the veins is by no means finally settled after all the years of study which have been devoted to the region. Into that abstruse problem I do not propose to enter, but it seems as though something should be said in regard to the origin of the most important country rock of the ores, the Cobalt conglomerate. W. L. Whitehead introduces his paper by a brief reference to the general geology in which he states his belief that the boulder conglomerate is of stream origin, basing this on the residual soils beneath it and the evidence of stratification often seen in the Cobalt series.

He does not explain, however, the way in which the supposed stream did its work. The conglomerate at Cobalt includes boulders of all sorts and shapes and sizes up to masses 5 feet by 3 feet by 3 feet weighing a ton or more, and in neighboring localities the same conglomerates contains still larger blocks, one at Timagami measuring 8 feet by 5 feet on the exposed surface, and weighing several tons.[1]

What kind of stream has Whitehead in mind as capable of transporting such rock masses miles from their source? Nothing short of a mountain torrent with a grade of hundreds of feet to the mile is sufficient for such powerful work. Is there any evidence of such a mountain valley or of such gradients in the

[1] "The Lower Huronian Ice Age," *Jour. Geol.*, Vol. XVI., p. 151.

region? On the contrary all students of the relations of the Cobalt conglomerate to the underlying Keewatin and Laurentian are agreed that the relief was slight, practically a peneplain, and Whitehead himself cuts down still further the very modest inequalities suggested by Miller and Knight in their excellent field work.

But this is not all. Boulder conglomerates of the same age resting on a similar peneplain are known at various points from Chibougamau in northern Quebec to the original Huronian, a breadth of nearly 500 miles. Did mountain torrents spread boulders over all these thousands of square miles?

Nothing of the sort happened, of course, and the evidences of water action in the Cobalt series indicate mainly standing water and not rivers, the slate interbedded with the conglomerate showing seasonal bandings of clay and silt such as one finds in the neighboring Pleistocene beds.

Whitehead has been unfortunate in his search for striated stones if the only ones he has seen were slickensided. Where there are slickensides or other evidences of crushing or faulting it is useless to look for glaciated stones, according to my own experience, since the delicate polish and striæ are almost sure to be destroyed under those conditions. That he should not have found the real thing is not surprising, since striated stones are by no means easy to extract from the hard matrix. A number of good examples may, however, be seen at the Royal Ontario Museum, Toronto. These have been examined by many expert glacial geologists, all of whom have been convinced of their glacial character; and during an excursion to Cobalt after the Geological Congress at Toronto, several good examples were secured by visiting geologists.

The matrix also is typically glacial as shown by thin sections and corresponds exactly with the matrix of strongly consolidated tillites of Permo-carboniferous age in South Africa and southern Argentina. In fact both thin sections and hand specimens from these localities are almost indistinguishable from those of Cobalt and the typical Huronian region. To one familiar with

ancient tillites the whole set of boulder conglomerates, slates and quartzites of the Cobalt Series can be perfectly matched in both Pleistocene and ancient glacial deposits, and the finding of typically ice-shaped, polished and straited stones in the conglomerate merely presents the final proof of what was almost certain from the field relations.

The Cobalt tillite is a rock of much economic importance, since its physical and probably chemical properties as an unweathered glacial deposit have led to the formation of 90 per cent. of the richest silver-bearing veins thus far discovered. The water-formed sediments, the slates and quartzites, and the eruptives of the Keewatin and the diabase of the great sill all lacked the features of the tillite which have made it the chief source of native silver in the most remarkable silver mining region in the world.

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# REVIEWS.

**Kaolin of Indiana.** By W. N. LOGAN, State Geologist. Indiana State Dept. of Conservation, Bull. No. 6, 1920, pp. 131, pls. 43, maps (colored) 7.

Beds of kaolin occur at several horizons at or near the top of the Mississippian formation in several counties in southwestern Indiana. One important horizon is at the contact between a Chester shale (below) and a Pottsville sandstone (above). All the beds are beneath a sandstone and above a shale. There has been only a slight commercial development of the deposits to date, in spite of the presence of large quantities of high-grade white clays. However, the deposits have not been well known. The present report should go far towards supplying the information desired by interested parties. It discusses (1) the physical and chemical properties of Indiana kaolin; (2) geological conditions of occurrence; (3) origin; (4) uses; (5) geographic distribution by counties. In this last chapter there are county maps showing outcrops, and a new topographic map of a township in Lawrence County in which several thick beds occur.

Dr. Logan made a special study of the mode of origin of Indiana kaolin. Several earlier explanations were disproven by a careful field study of the several deposits. Laboratory experiments and microscopic examinations have established that this kaolin is due to bio-chemical action. Such an origin of kaolin has not before been suspected. It was found that under proper conditions in the laboratory, sulphur bacteria secrete kaolin. In nature, sulphur bacteria obtain sulphur from the iron pyrite in the shale. The sulphuric acid which is formed, attacks the aluminum in the shale. The resulting compound reacts with the quartz of the sandstone, and the sulphur is replaced by silica, producing kaolin.

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# SCIENTIFIC NOTES AND NEWS[1]

W. S. BAYLEY, of the University of Illinois, who has been completing an investigation of the iron ores of North Carolina under the joint auspices of the U. S. Geological Survey and the North Carolina Survey, has returned to Urbana, Illinois.

GILBERT H. CADY, who has been connected with the Geological Survey of Illinois for several years and who has recently returned from a year spent in mining interests in the far east, has accepted the position of professor of geology, and head of the department, in the University of Arkansas. He also becomes State Geologist of Arkansas.

W. T. THOM, JR., of the U. S. Geological Survey, is now in Montana studying the structural features of the lignite fields in the northeastern part of the state.

H. F. CROOKS, assistant professor of geology at the Colorado School of Mines, investigated possible oil lands for Eastern interests during July. He spent August at Bonanza, Colorado, examining the properties of the Antoro Mines Co.

KIRK BRYAN, of the U. S. Geological Survey, and G. E. P. Smith, Irrigation Engineer in the Agricultural Experiment Station, University of Arizona, will make a joint investigation of the ground water resources of the San Pedro Valley, Arizona, under a coöperative agreement. Field work will begin about September 15.

D. E. WINCHESTER, with headquarters in Denver, is now in charge of oil shale operations of the Carter Oil Co.

[1] Geologists, mining engineers and others interested in applied geology are invited to keep the editor informed of new investigations of mining districts or scientific studies undertaken by them, together with such other scientific and personal items as may come to their notice.

T. NELSON DALE, who has been engaged in economic studies of building stones, will retire from the U. S. Geological Survey at an early date, under the Act for Retirement of Government Employees.

H. S. GALE has resigned from the U. S. Geological Survey to enter the employ of the Corning Glass Co.

CHARLES T. KIRK, of the firm of Kirk and Hoover, geologists, has returned to Tulsa, Oklahoma, from a five months' trip in Central and South America.

AS PART of the plan to popularize the National Parks, F. E. Mathes, of the U. S. Geological Survey, is conducting a selected body of boy scouts on a two months' tour of the parks.

FREDERICK F. RANSOM is engaged in geological work in the oil fields near Santa Maria, California.

CHARLES BUTTS, of the U. S. Geological Survey, left Washington in July for further study of the stratigraphy of the Mississippian in eastern Kentucky.

WALDEMAR T. SCHALLER has severed his connection with the Great Southern Sulphur Co., Inc., of New Orleans, La., and has returned to the U. S. Geological Survey.

H. W. TURNER is in Arizona on examination work.

W. PROUTY, geologist for the Old Dominion company at Globe, has been appointed chief geologist for the Copper Queen branch of the Phelps Dodge Corporation at Bisbee.

F. L. HESS, of the U. S. Geological Survey, has returned to the United States from South America.

H. A. C. JENSEN, of the Mineral Resources Branch of the U. S. Geological Survey, is now in the West making a statistical study of several large copper mines.

WARREN D. SMITH is taking a year's leave of absence from the University of Oregon, in order to return to the Philippines to take charge of the Division of Mines, Philippine Bureau of Sci-

ence, Manila. En route he attended the Pan-Pacific Scientific Congress, August 2, 1920, in Honolulu. He will return to the University of Oregon October 1, 1921.

F. C. CALKINS, of the U. S. Geological Survey, left Washington July 29 for field work in Alta, Utah.

BRUCE WHITE was at the head of a geological party doing oil work in central Montana during the summer.

G. B. RICHARDSON, with the assistance of K. K. Kimball, both of the U. S. Geological Survey, are mapping the New Kensington Quadrangle, Pa.

A. G. BURRITT, geologist, and H. A. Linke, engineer, both of Salt Lake City, have been making a geological Survey of the Fossil oilfields near Kemmerer, Wyoming.

M. L. BANCROFT, of the Geological Survey of Canada, is carrying on geological work in the Lardeau district of British Columbia.

J. P. BUWALDA, of the U. S. Geological Survey, has been doing coöperative work with the Idaho State Bureau of Mines and Geology in the study of the Tertiary basins of the western part of that state, giving special attention to the areas favorable for the occurrence of oil and gas.

CHARLES H. FULTON, formerly professor of metallurgy in the Case School of Applied Science, has now accepted the directorship of the Missouri School of Mines, at Rolla.

DR. F. C. COTTRELL, Director of the Bureau of Mines, has been granted the Willard Gibbs Medal of the Chicago Section of the American Chemical Society.

THE following well-known members of the U. S. Geological Survey, though eligible for retirement under the new law, will be continued in service for the next two years: H. C. Rizer, Chief Clerk; Frank Wigglesworth Clarke, Chemist; J. S. Diller, Geologist; C. G. Yale, Statistician; and G. M. Wood, Editor.

C. E. VAN ORSTRAND devoted part of the summer to observing deep-well temperatures in the oil fields of various states.

MARIUS R. CAMPBELL spent the first two weeks of August near Blacksburg, Va., in a study of the Pocono coals.

HOYT S. GALE, after six months in South America, has re signed from the U. S. Geological Survey to enter the employ of the Corning Glass Co.

EDWIN E. CHASE, of Chase and Sons, mining and geological engineers, of Denver, has been in Wyoming doing professional work.

CHESTER R. LONGWELL, of Yale University, has undertaken a study of the limestones of eastern New York and western Connecticut for the U. S. Geological Survey.

LESTER S. GRANT, professor of mining in the Colorado School of Mines, visited several mining and metallurgical plants in Utah during the summer.

C. E. DOBBIN, of the U. S. Geological Survey, left Washington August 12 to make a geological reconnaissance in the Powder River region, Montana and Wyoming.

ROBERT S. LEWIS, Professor of Mining and Metallurgy in the University of Utah, is investigating copper deposits in Alaska for the U. S. Bureau of Mines. He will return to Utah in October.

JOHN D. NORTHRUP, of Cheyenne, Wyoming, sailed on August 28 for Peru, where he will spend two years in oil-field examinations.

C. Y. HSIEH, a member of the Geological Survey of China, has been employed temporarily by the U. S. Geological Survey, and is now working with A. E. Fath in the Lost Soldier oil field of Wyoming.